U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-259 088

Assessment of the Air Quality Impact of SO2 Emissions from the ASARCO-Tacoma Smelter

H. E. Cramer Co., Inc, Salt Lake City, Utah

Prepared for

Environmental Protection Agency, Seattle, Wash Region X

Jul 76

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA 910/9-76-028	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE ASSESSMENT OF THE AIR QUALITY IMPACT OF SO_2 EMISSIONS FROM THE ASARCO-TACOMA SMELTER		5. REPORT DATE July 1976 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) H. E. Cramer, J. F. Bowers and H. V. Geary		8. PERFORMING ORGANIZATION REPORT NO. TR-76-105-01
9. PERFORMING ORGANIZATION NAME AND ADDRESS H. E. Cramer Company, Inc. P. O. Box 8049 Salt Lake City, Utah 84108		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. Contract No. 68-02-1387 Task Order No. 4
12. SPONSORING AGENCY NAME AND ADDRESS U. S. Environmental Protection Agency, Region X 1200 Sixth Avenue Seattle, Washington 98101		13. TYPE OF REPORT AND PERIOD COVERED Final June 1975 - June 1976 14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

The major purpose of the work described in this report was to use diffusion modeling techniques to calculate the impact on ambient air quality of SO_2 emissions from the ASARCO copper smelter in Tacoma, Washington for the existing smelter configuration (51-percent constant emissions control) and for 20 alternative smelter configurations with varying degrees of constant emissions control. The accuracy of the modeling techniques was established by the close correspondence obtained between calculated and observed short-term ground-level SO_2 concentrations for 20 selected historical cases, when high hourly SO_2 concentrations were measured in the area surrounding the smelter, as well as by the close agreement between calculated and observed annual average concentrations for 1972. The results of the model calculations show that the maximum allowable constant SO_2 emission rate consistent with maintaining the Washington Department of Ecology (DOE) and Puget Sound Air Pollution Control Agency (PSAPCA) air quality standards ranges from 2000 to 2500 pounds per hour, depending on the source configuration. These same SO_2 emission rates will also preclude violations of the National SO_2 air quality standards. A review of the ASARCO Supplementary Control System (SCS) shows that it has been effective in eliminating almost all violations of the National short-term SO_2 air quality standards. However, as evidenced by air quality measurements to date, we believe the ASARCO SCS is not a viable method for preventing violations of the PSAPCA and DOE 5-minute and 1-hour SO_2 standards.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Copper Diffusion Models Exhaust Gases Meteorology Monitor	Smelters Sulfur Dioxide		

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 222
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE 7.75

EPA Form 2220-1 (9-73)

307036

EPA 910/9-76-028
July 1976

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Final Report

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NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA 910/9-76-028
July 1976

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Contract No. 68-02-1387
Task Order No. 4
EPA Project Officer: D. A. Wilson

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SALT LAKE CITY, UTAH 84108

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This report was furnished to the Environmental Protection Agency by the H. E. Cramer Company, Inc. of Salt Lake City, Utah in fulfillment of EPA Contract No. 68-02-1387, Task Order No. 4. This report has been reviewed by Region X, EPA and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Region X Publication No. EPA 910/9-76-028

ACKNOWLEDGEMENTS

Throughout the program of work culminating in the preparation of this report, the H. E. Cramer Company, Inc. has greatly benefited from the assistance, cooperation and guidance provided by many individuals.

We are especially indebted to Mr. Dean Wilson, EPA Region X Meteorologist and our Project Officer. Mr. Wilson assisted us in obtaining the data required for our study, closely monitored the progress of our study, and coordinated our contacts with EPA Region X and the Puget Sound Air Pollution Control Agency (PSAPCA). Others within EPA Region X who provided guidance during the course of our study include: Mr. G. Hofer, Chief, Air Surveillance and Investigation Section; Mr. C. Findley, Chief, Air Technical Section; and Mr. R. Malatesta, Technical Advisor. Mr. L. Sims, Chemical Engineer, assisted in the development of source and emissions data for the possible future configurations of the ASARCO smelter. Mr. W. Russell, Meteorologist, situated a continuous SO_2 monitor within an area of predicted high short-term SO_2 concentrations and operated the monitor for a four-month period.

We are also greatly indebted to Mr. A. Dammkoehler, Air Pollution Control Officer of PSAPCA, and to the members of his professional staff for their assistance and cooperation. Mr. A. Kellogg, Chief-Technical Services; Mr. M. Svoboda, Senior Meteorologist and Data Analyst; and Mr. K. Knechtel, Meteorologist and Systems Analyst, provided us with copies of the various ASARCO reports to PSAPCA and with PSAPCA meteorological and air quality data. The historical cases modeled in this study were, to a large extent, selected on the basis of the recommendations of these gentlemen. Also, we wish to thank Mr. J. Roberts, Air Pollution Engineer, for his assistance in obtaining emissions data for the ASARCO smelter and the other major SO_2 sources in the Seattle-Tacoma area.

Finally, we wish to acknowledge the cooperation and assistance of the personnel of the ASARCO-Tacoma Copper Smelter. Specifically, Mr. R. Welch provided detailed information about the operation of the smelter's Supplementary Control System and Mr. C. Randt provided detailed information about plant operations and emissions.

EXECUTIVE SUMMARY

The assessment of the air quality impact of SO_2 emissions from the ASARCO copper smelter in Tacoma, Washington described in this report was divided into four phases:

- Background Study
- Model Development
- Model Application
- Evaluation of the ASARCO Supplementary Control System (SCS)

The Background Study Phase consisted of a review of all available meteorological and air quality data for the Seattle-Tacoma area and of all available SO_2 emissions data for the ASARCO smelter and other major SO_2 sources. In addition, ASARCO SCS procedures were studied, previous diffusion studies of the air quality impact of SO_2 emissions from the ASARCO smelter were analyzed and various diffusion models were studied to determine those most likely to be applicable to the ASARCO smelter. On the basis of this review, three critical meteorological regimes were identified as being conducive to the highest short-term ground-level SO_2 concentrations resulting from ASARCO stack emissions. The critical wind-speed condition (moderate-to-strong winds in combination with neutral stability) was determined to be the meteorological regime most likely to lead to maximum 3-hour and 24-hour ground-level SO_2 concentrations. The limited-mixing condition (light-to-moderate winds with the ASARCO plume contained within a relatively shallow surface mixing layer) was found to be the meteorological regime most frequently associated with violations of the 5-minute and 1-hour PSAPCA standards. The fumigation condition was found to result in the simultaneous occurrence of high ground-level SO_2 concentrations at many points in the Seattle-Tacoma area. One long-term diffusion model was selected to calculate average annual concentrations and five short-term diffusion models were selected to calculate concentrations during the three critical meteorological regimes.

In the Model Development Phase, the validity of the long-term diffusion model was tested by using it with 1972 meteorological data and emissions data for ASARCO and the other major SO_2 sources in the Seattle-Tacoma area to calculate annual average concentrations at the various SO_2 monitor sites. In these calculations, the effects of the ASARCO Supplementary Control System (SCS) on SO_2 emissions were simulated by assigning an average emission rate, based on an analysis of the 1972 smelter curtailment reports, to each joint combination of Pasquill stability category and wind-speed category. The calculated and observed 1972 annual average SO_2 concentrations at all monitors in the Tacoma area (except the ASARCO monitor at N26th and Pearl) differed by less than one-half the monitor threshold and accuracy (i.e., by less than ± 0.005 parts per million). To test the validity of the short-term models and to determine the models best suited for application in this study, emissions data and meteorological data were obtained for 20 selected cases during the 3-year period from 1972 through 1974 when high SO_2 concentrations of one hour or longer duration were observed at SO_2 monitors. The 20 cases, which were selected with the assistance of PSAPCA personnel, included meteorological conditions representative of all three critical meteorological regimes. The emissions and meteorological data were used with the short-term models to calculate SO_2 ground-level concentrations at air quality monitor sites for each case. These calculated concentrations were then compared with the corresponding observed SO_2 concentrations. In the case of the model selected for the limited-mixing and critical wind-speed conditions, the average ratio of the calculated and observed hourly concentrations was unity (all observed hourly concentrations considered in the comparison were above the PSAPCA 1-hour standard of 0.25 parts per million). With respect to the model selected for the fumigation condition, the average ratio of the calculated and observed concentrations for the period of fumigation was equal to 0.8. The calculated maximum hourly fumigation concentrations were approximately one-half the observed hourly maximums. We believe this is principally explained by the assumption made in the model calculations--in the absence of requisite wind observations--that the wind-direction distribution at plume height prior to the occurrence of fumigation is circular. It is important to note that all of the long-term and short-term diffusion-model calculations were made without recourse to calibration constants or any other arbitrary adjustment techniques. The Model Development Phase thus established the validity of the selected modeling techniques for estimating the impact of ASARCO SO_2 emissions in the Seattle-Tacoma area.

In the Model Application Phase, the validated modeling techniques were used to calculate maximum long-term and short-term ground-level SO_2 concentrations for 21 Control Alternatives comprising the existing smelter configuration without SCS and 20 hypothetical smelter configurations with varying degrees of constant emissions control. Table I gives, for each Control Alternative, the total SO_2 emission rate, the approximate percent constant SO_2 emissions control as well as a brief description of the emissions controls and source configuration. From discussions with PSAPCA and EPA Region X, it appears that ASARCO has actually been able to achieve only about 45 percent constant emissions control for Control Alternative 1 (the existing smelter configuration without SCS) instead of the 51 percent given in Table I because the operating efficiency of present emissions control equipment is below design specifications. Tables II and III respectively identify the Control Alternatives that will meet, without any SCS, the National and the PSAPCA and Washington Department of Ecology SO_2 air quality standards. The Washington Department of Ecology (DOE) standards are essentially the same as the PSAPCA standards. As shown in Table II, Control Alternatives 7, 8, 9, 10, 20 and 21 meet all the National SO_2 air quality standards. Similarly, Table III shows that Control Alternatives 7, 9, 20 and 21 also meet all PSAPCA and

TABLE I

DESCRIPTION OF THE ASARCO CONTROL ALTERNATIVES

Control Alternative	Total SO_2 Emission Rate (lb/hr)	Percent Constant Emissions Control	Description
1	24,802	51	Existing source configuration without SCS.
2	24,802	51	Existing emissions controls with separate stacks for the existing acid plant and liquid SO_2 plant.
3	24,802	51	Existing emissions controls using new main stack and modifications outlined in ASARCO variance application.
4	14,490	71	Existing emissions controls on reverbs and converters, new acid plant on roasters after enrichment by SO_2 injection, existing main stack and modifications outlined in ASARCO variance application.
5	14,250	72	Existing emissions controls on reverbs and converters, scrubber on roasters, existing main stack and modifications outlined in ASARCO variance application.
6	14,250	72	Same as Control Alternative 5 with a new main stack.
7	1,900	96	Electric arc furnace with acid plant on roasters and part of converter stream after enrichment by SO_2 injection, liquid SO_2 plant on remainder of converter stream, existing main stack and modifications outlined in ASARCO variance applications
8	1,900	96	Same as Control Alternative 7 with a new main stack.

TABLE I (continued)

DESCRIPTION OF THE ASARCO CONTROL ALTERNATIVES

Control Alternative	Total SO_2 Emission Rate (lb/hr)	Percent Constant Emissions Control	Description
9	2,240	96	Existing configuration with scrubber on roaster and reverb streams, existing main stack and modifications outlined in ASARCO variance application.
10	2,240	96	Same as Control Alternative 9 with a new main stack.
11	24,750	51	Existing emissions controls with modifications outlined in ASARCO variance application.
12	24,750	51	Same as Control Alternative 11 with a new main stack.
13	22,840	55	Existing emissions controls with 20 percent of roaster stream through existing acid plant after enrichment by SO_2 injection, existing main stack and modifications outlined in ASARCO variance application.
14	22,840	55	Same as Control Alternative 13 with a new main stack.
15	19,750	61	Liquid SO_2 plant and existing acid plant control converter stream, new acid plant controls 50 percent of roaster stream after enrichment by SO_2 injection, existing main stack and modifications outlined in ASARCO variance application
16	19,750	61	Same as Control Alternative 15 with a new main stack.

TABLE I (continued)

DESCRIPTION OF THE ASARCO CONTROL ALTERNATIVES

Control Alternative	Total SO_2 Emission Rate(lb/hr)	Percent Constant Emissions Control	Description
17	14,160	72	Liquid SO_2 plant on part of converter stream, new acid plant on remainder of converter stream and 100 percent of roaster stream after enrichment by SO_2 injection, existing main stack and modifications outlined in ASARCO variance application.
18	12,730	75	Existing emissions controls on converter stream, new acid plant on reverb stream after enrichment by SO_2 injection, existing main stack.
19	12,400	76	Liquid SO_2 plant on part of converter stream, new acid plant on remainder of converter stream and reverb stream after enrichment by SO_2 injection, existing main stack.
20	2,470	95	Existing emissions controls on converter stream, roaster and reverb stream to new acid plant following enrichment by SO_2 injection, existing main stack.
21	2,230	96	Existing emissions controls on converter stream, electric arc furnace stream combined with roaster stream to a new acid plant following enrichment by SO_2 injection, existing main stack.

TABLE II

CONTROL ALTERNATIVES THAT WILL MEET THE NATIONAL AMBIENT AIR QUALITY STANDARDS FOR SO_2

Control Alternative	National Air Quality Standards for SO_2		
	Annual Standard (0.03 ppm)	3-Hour Standard (0.50 ppm)	24-Hour Standard (0.14 ppm)
1	X		
2			
3			
4	X	X	
5	X	X	
6	X		
7	X	X	X
8	X	X	X
9	X	X	X
10	X	X	X
11	X		
12			
13	X		
14			
15	X		
16	X		
17	X	X	
18	X	X	
19	X	X	
20	X	X	X
21	X	X	X

TABLE III

CONTROL ALTERNATIVES THAT WILL MEET THE PSAPCA AMBIENT AIR QUALITY STANDARDS FOR SO_2

Control Alternative	PSAPCA Air Quality Standards for SO_2					
	Annual Standard (0.02 ppm)	Monthly Standard (0.04 ppm)	24-Hour Standard (0.10 ppm)	1-Hour Standard (0.40 ppm)	1-Hour Standard (0.25 ppm)	5-Minute Standard (1.0 ppm)
1	X	X				
2						
3						
4	X	X				
5	X	X				
6						
7	X	X	X	X	X	X
8	X	X	X	X	X*	X
9	X	X	X	X	X	X
10	X	X	X	X	X*	X
11	X	X				
12						
13	X	X				
14						
15	X	X				
16						
17	X	X				
18	X	X				
19	X	X				
20	X	X	X	X	X	X
21	X	X	X	X	X	X

* Marginal compliance, infrequent violations possible.

Washington DOE standards. Control Alternatives 8 and 10, as indicated in Table III, are marginal with respect to compliance with the PSAPCA 1-hour standard of 0.25 parts per million. Although the model calculations clearly indicate that any violoations of this standard would be infrequent, we were unable to eliminate the possibility that the standard might be exceeded at any point more than twice in any 7-day period. As shown in Table I, the Control Alternatives that meet all National, PSAPCA and Washington DOE standards all have SO_2 emission rates ranging from about 2000 to 2500 pounds per hour, depending on the source configuration. These SO_2 emission rates correspond approximately to 96 and 95 percent constant emissions control based on the emission rate of 24,802 pounds of SO_2 per hour (51-percent control) for Control Alternative 1.

The ASARCO SCS curtails SO_2 emissions and/or uses stack heaters to increase plume rise whenever high ground-level SO_2 concentrations that threaten the short-term standards are either anticipated or observed to occur at the ASARCO and/or PSAPCA monitors. According to our calculations, the maximum decrease in ground-level SO_2 concentrations that can normally be achieved through the use of the stack heaters alone varies from about 14 to 19 percent, depending on whether one or both stack heaters are used. A severe constraint in the use of the ASARCO SCS to achieve the stringent 5-minute and 1-hour PSAPCA SO_2 standards arises from an inherent minimum time delay, which varies from about 20 minutes to 1 hour or longer, between the time a curtailment decision is made and the time the decision is implemented and the reduction in emissions can affect ambient air quality at SO_2 monitors in the Tacoma area. It follows that it is generally not possible for the ASARCO SCS to prevent violations of the PSAPCA 5-minute and 1-hour standards on the basis of telemetered air quality observations from the ASARCO and PSAPCA monitoring networks. Instead, occurrences of high 5-minute and 1-hour concentrations at monitor locations must be anticipated and curtailment decisions must be made by the ASARCO SCS at least 20 minutes to 1 hour in advance of such occurrences. As discussed below, although the ASARCO meteorologists have become highly skilled in anticipating the occurrence of high SO_2 concentrations, many violations of the PSAPCA 5-minute and hourly standards continue to occur. The time-delay constraint in the operation of the ASARCO SCS is generally not limiting in the case of the 3-hour and 24-hour National standards and thus telemetered air quality monitor observations can normally be used effectively as a basis for curtailments required to meet these standards.

The effectiveness of the ASARCO SCS in preventing violations of the National and PSAPCA SO_2 short-term standards is shown in Tables IV and V which list the total number of violations per year observed at the PSAPCA monitor located at N26th and Pearl. This monitor has been in operation continuously since 1968 and is the monitor most frequently affected by ASARCO emissions. As shown in Table IV, no violations of the National standards were observed at the monitor after 1971 (the SCS was started in 1970) until the first part of 1976 when one violation of the 3-hour standard occurred. Also, although there were no violations of the 24-hour National standard, there was one observation above the standard and one observation equal to standard during the first part of 1976. The success of the ASARCO SCS in preventing almost all violations of the National short-term standards is in part due to the curtailment actions and stack-heater operations undertaken in attempting to meet the more stringent PSAPCA short-term standards.

Table V shows that the number of violations of the PSAPCA short-term standards decreased dramatically from 1970 through 1973. Since 1973, however, no appreciable decrease in the number of violations has occurred in spite of the addition in 1974 of a liquid SO_2 plant which increased the constant emissions control from 17 to 51 percent. We believe that Table V shows that the ASARCO SCS reached a limit of effectiveness during 1973 and 1974. We also believe that,

TABLE IV

TOTAL NUMBER OF VIOLATIONS OF THE NATIONAL AIR QUALITY STANDARDS FOR SO_2 AT N26th AND PEARL

Year	Number of Violations*	
	3-Hour Secondary Standard	24-Hour Primary Standard
1976**	1 (2)	0 (1)***
1975	0 (0)	0 (0)
1974	0 (1)	0 (0)
1973	0 (0)	0 (0)
1972	0 (0)	0 (0)
1971	1 (2)	1 (2)
1970	5 (6)	1 (2)
1969	5 (6)	4 (5)
1968	0 (1)	1 (2)

* Total number of observations above the standard are enclosed by parentheses

** As of 6 February 1976

*** One observed concentration exactly equal to the 24-hour standard also occurred during 1976

TABLE V

TOTAL NUMBER OF VIOLATIONS OF THE PSAPCA AIR QUALITY STANDARDS FOR SO_2 AT N26th AND PEARL

Year	Number of Violations			
	5-Minute Standard of 1.0 ppm	1-Hour Standard of 0.40 ppm	1-Hour Standard of 0.25 ppm	24-Hour Standard of 0.10 ppm
1976*	10	10	15	2
1975	8	6	35	0
1974	10	6	21	1
1973	16	4	27	0
1972	27	11	34	0
1971	39	20	52	3
1970	169	62	140	4
1969	199	84	219	15
1968	124	56	125	10

* As of 6 February 1976

because of the severe delay-time constraint and the consequent dependence of curtailment decisions on meteorological forecasts of plume behavior, it is extremely unlikely that any further significant reductions in the number of violations of the PSAPCA 5-minute and 1-hour standards can be achieved by SCS techniques with the present source configuration and 51-percent constant emissions control. In our opinion, with the present source configuration, violations of the PSAPCA 5-minute and 1-hour standards can only be prevented by reducing the maximum allowable stack emissions to about 2500 pounds of SO_2 per hour. This is approximately equal to the constant hourly emission rate for the Control Alternatives in Tables II and III that meet all the National and PSAPCA SO_2 standards.

In summary, the principal conclusions of this study are:

- Without the use of SCS, the present smelter source configuration (51-percent constant emissions control) would result in violations of all National, PSAPCA and Washington DOE short-term (5-minute, 1-hour, 3-hour and 24-hour) SO_2 air quality standards
- Depending on the source configuration, the maximum allowable SO_2 emission rate consistent with maintaining all PSAPCA and Washington DOE air quality standards for SO_2 ranges from 2000 to 2500 pounds per hour; these same emission rates will also ensure compliance with all National air quality standards for SO_2
- The ASARCO SCS is capable of preventing most violations of the National 3-hour and 24-hour air quality standards, but SCS is not a viable means of preventing violations of the more stringent PSAPCA 5-minute and 1-hour standards

Recommendations made in this report include:

- Investigation of the impact of low-level fugitive SO_2 emissions and possible stack downwash, accomplished in part by the installation and operation of additional SO_2 monitors in the Tacoma area, located closer to the smelter than the existing monitors.
- Inclusion by ASARCO in the smelter operation reports submitted to PSAPCA of average hourly values of the stack exit temperature, actual volumetric flow rate and SO_2 emission rate in pounds per hour
- Change of the format of the ASARCO curtailment reports to PSAPCA so that curtailment requests are expressed as a maximum allowable SO_2 emission rate in pounds per hour rather than as a percent curtailment
- Investigation of the impact of SO_2 emissions from the Kaiser aluminum plant in Tacoma which, according to our diffusion-model calculations, may be threatening the National and PSAPCA SO_2 air quality standards

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SECTION 1
INTRODUCTION

1.1 BACKGROUND

The American Smelting and Refining Company (ASARCO) copper smelter in Tacoma, Washington is one of the largest copper smelters in the United States, currently accounting for about eight percent of the nation's copper. The smelter, which was acquired by ASARCO in 1905, began as a lead smelter in 1890 with copper smelting added in 1902. In 1911, lead smelting was discontinued in favor of copper smelting. Copper has been the principal product of the Tacoma plant since 1911.

Copper smelting at the Tacoma plant has always resulted in substantial emissions to the atmosphere of sulfur dioxide (SO_2). During the first 60 years of operation, a tall stack was the principal method used to reduce the impact on ambient air quality of these emissions. In 1950 an acid plant was installed which recovered 17 percent of the total SO_2 generated by smelting the copper ore concentrate. The addition of a liquid SO_2 plant in 1974 increased the percentage of SO_2 recovery to a maximum of 51 percent. According to EPA Region X and PSAPCA personnel, the smelter recovers on the average only about 45 percent of the generated SO_2 because the emissions control equipment operates below design efficiency.

Figure 1-1 is a topographic map of the Tacoma area. The filled circle near the tip of the Tacoma peninsula shows the location of the ASARCO smelter's main stack. As shown by the figure, terrain elevations in the area surrounding the ASARCO smelter range from sea level to about 150 meters (500 feet) above sea level. Water surrounds the smelter on three sides, and the land surface varies from relatively smooth tidal flats and beaches to rugged hills. The meteorology and complex topography of the Tacoma area frequently combine to produce poor

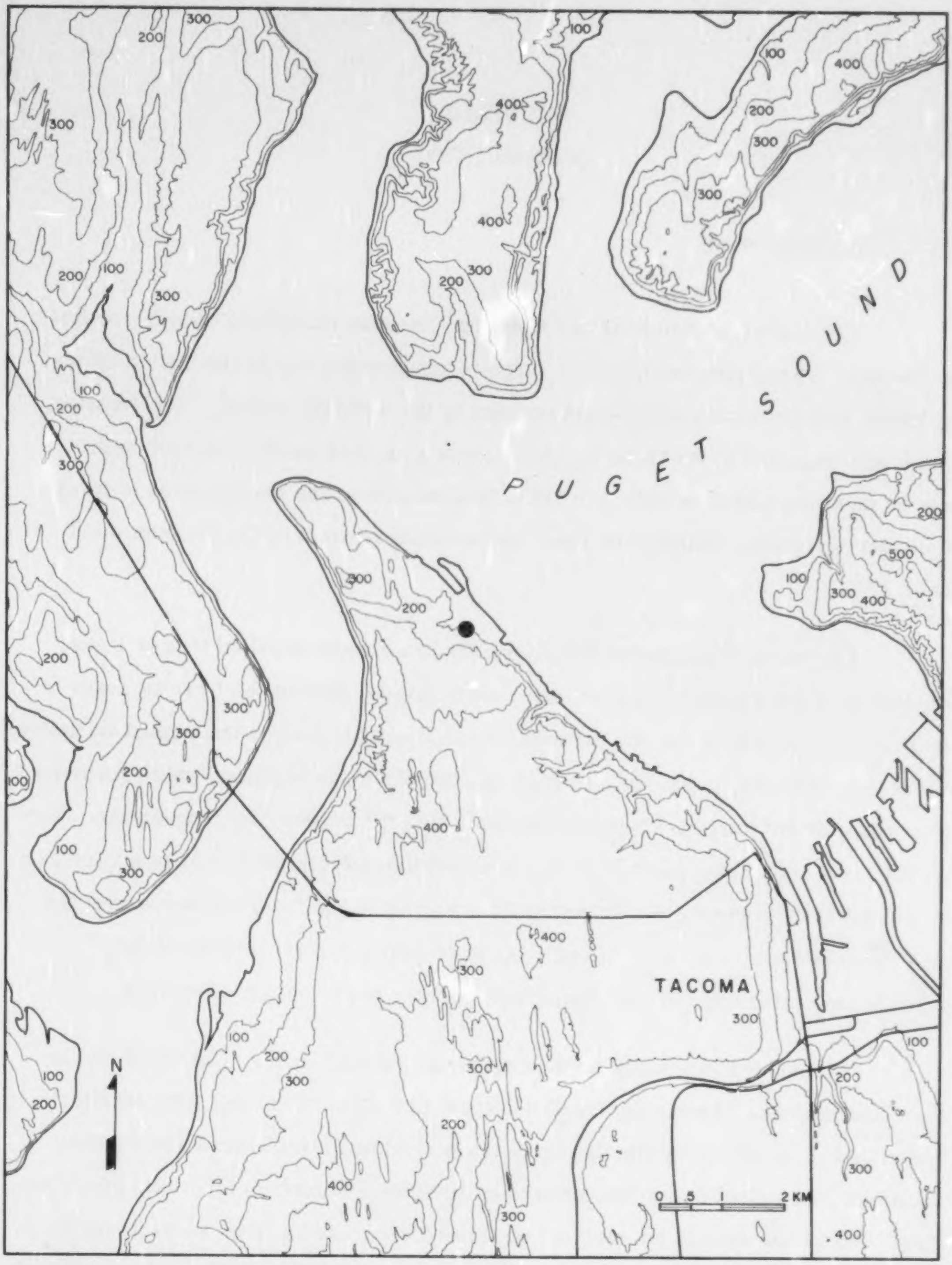

FIGURE 1-1. Topographic map of the Tacoma area. The filled circle shows the location of the main ASARCO stack. Terrain elevations are in feet above mean sea level, and the contour interval is 100 feet (30.5 meters).

atmospheric dilution conditions (i.e., conditions that are conducive to high ground level SO_2 concentrations as a result of the smelter's emissions).

For many years, the ASARCO Tacoma smelter voluntarily curtailed plant operations when meteorological conditions were conducive to ground-level SO_2 concentrations that endangered vegetation or caused public complaints. Prior to 1969, curtailment decisions at the Tacoma smelter were made by the plant manager. Thus, this form of intermittent curtailment came to be known as "Sea-Captaining." In late 1969, the Tacoma smelter employed a professional meteorologist to develop and operate an Intermittent Control System (ICS), now called a Supplementary Control System (SCS), in order to improve the ambient air quality in the vicinity of the smelter.

Serious attempts to apply emissions and air quality standards to the Tacoma smelter began with the formation of the Puget Sound Air Pollution Control Agency (PSAPCA) on 1 July 1967. On 13 March 1968, PSAPCA adopted Regulation I which included emissions and air quality standards for SO_2. However, civil penalties for violations of Regulation I were not assessed until July 1969. On 29 December 1969 ASARCO applied for a variance from the ambient air quality standards for SO_2. This variance was subsequently denied by PSAPCA, but ASARCO petitioned for judicial review. On 8 July 1970, PSAPCA revised Regulation I to include the more stringent Washington Department of Ecology (DOE) air quality standards and to limit sulfur emissions to 10 percent of the total sulfur generated during the smelting process. After public hearings, the PSAPCA Board granted ASARCO a three-year variance from the new emissions standard on 13 January 1971. This variance was appealed by ASARCO to the Pollution Control Hearing Board (PCHB). The PCHB remanded the problem to the PSAPCA Board which, after a public hearing, granted a variance that would terminate on 31 January 1976 if ASARCO did not commit to control 90 percent of the input sulfur. On 9 December 1974, ASARCO notified PSAPCA that the smelter did not intend to comply with the PSAPCA 10-percent SO_2 emissions standard. In February 1976 the PSAPCA Board granted the smelter a new five year variance from the 10-percent SO_2 emissions standard. As part of the agreement, ASARCO promised to commit nearly $4.7 million toward additional emissions controls for pollutants other than SO_2.

The U. S. Environmental Protection Agency (EPA) has also been concerned about the air quality impact of the Tacoma smelter's emissions, including SO_2, particulates and arsenic. In June 1975, EPA contracted with the H. E. Cramer Company, Inc. of Salt Lake City, Utah to study the impact on ambient air quality of SO_2 emissions from the smelter and to evaluate the effectiveness of the smelter's Supplementary Control System in preventing violations of SO_2 air quality standards.

1.2 PURPOSE AND APPROACH

The primary purpose of the study described in this report was to use diffusion modeling to determine the degree of constant SO_2 emissions control required for the ASARCO-Tacoma smelter to assure attainment and maintenance of the National, Washington DOE and PSAPCA air quality standards listed in Table 1-1. An additional purpose was to evaluate the reliability of the ASARCO Supplementary Control System (SCS).

The study consisted of four phases. During Phase I, a background study was conducted to review meteorological and air quality data, ASARCO SCS procedures, previous efforts to model smelter SO_2 emissions, and emissions data for ASARCO and the other major SO_2 sources in the Seattle-Tacoma area. During Phase II, one long-term and five short-term diffusion models were tested to determine the models most applicable to the unique topographical and meteorological conditions in the vicinity of the ASARCO smelter. Phase III consisted of the application of the models selected during Phase II to determine the degree of constant emissions control required to meet the various air quality standards listed in Table 1-1. Finally, the reliability of the ASARCO SCS program was assessed during Phase IV in order to determine whether the smelter's SCS is a viable method of maintaining the applicable air quality standards.

1.3 REPORT ORGANIZATION

In addition to the Introduction, this report consists of six major sections and four appendices. Section 2 contains descriptions of the past and present stack and emissions data for the ASARCO smelter as well as stack and emissions data for possible future smelter configurations. Section 3 contains a discussion of the meteorology of the Seattle-Tacoma area, descriptions of the meteorological regimes associated with the highest ground-level SO_2 concentrations and listings of the meteorological input parameters used in the diffusion-model calculations. Section 4 presents the results of calculations of annual average SO_2 concentrations in Tacoma for the year 1972 and the results of calculations for 20 Short-Term Historical Cases when high SO_2 concentrations were observed for one or more hours at air quality monitors; comparison of calculated and observed concentrations is also included in Section 4. In Section 5, the modeling techniques used in Section 4 are employed to assess the impact on ambient air quality of both current smelter SO_2 emissions (without the use of SCS) and smelter emissions for possible future plant configurations. An evaluation of the effectiveness of the smelter's SCS is presented in Section 6. The conclusions and recommendations of the study are given in Section 7.

The diffusion models used in this study are described in detail in Appendix A. Appendix B provides tabulations of the annual frequency of occurrence of wind-speed and wind-direction categories in Tacoma, classified according to the Pasquill stability categories. Emissions data for the major SO_2 sources in the Tacoma area,

TABLE 1-1

SO_2 AIR QUALITY STANDARDS APPLICABLE TO THE ASARCO SMELTER

Time Period	National Standards (ppm)		Washington DOE Standards (ppm)	PSAPCA Standards (ppm)
	Primary	Secondary		
5 minutes	--	--	---	1.00[d]
1 hour	--	--	0.40[a]	0.40[b]
1 hour	--	--	0.25[c]	0.25[c]
3 hours	--	0.50[a]	---	---
24 hours	0.14[a]	--	0.10[a]	0.10[b]
30 days	--	--	---	0.04[b]
Annual	0.03[b]	--	0.02[b]	0.02[b]

a--Not to be exceeded more than once per year

b--Never to be exceeded

c--Not to be exceeded more than two times in any seven consecutive days

d--Not to be exceeded more than once in any eight consecutive hours other than the ASARCO smelter, are given in Appendix C. Appendix D contains a discussion of exit-velocity restrictions on buoyant plume rise for stacks in general and for the main ASARCO stack in particular. Appendix E contains detailed discussions of the 20 Short-Term Historical Cases.

SECTION 2

SO_2 EMISSIONS DATA FOR THE ASARCO TACOMA SMELTER

The basic SO_2 emissions data used in this study are for normal smelter operations at full production with the following percent constant emissions control:

- 17 percent--applies to smelter operations prior to March 1974
- 51 percent--applies from March 1974 to present
- $\geq$51 percent--applies to possible future smelter configurations used in Control Alternative Calculations to determine the degree of constant emissions control required for compliance with air quality standards

SO_2 emissions data for 17-percent constant emissions control were supplied by ASARCO and are estimates derived from material balance calculations. These estimates were obtained by forming ratios of the total weight of sulfur contained in the slag, copper, copper by-products, and sulfuric acid produced by the smelter to the total weight of sulfur contained in the copper ore prior to processing. For a sulfur balance, the difference between the total weight of sulfur in the ore and the weight of the sulfur contained in the slag and smelter by-products must equal the weight of the sulfur contained in the SO_2 discharged to the atmosphere. Calculations of the amount of sulfur discharged to the atmosphere through the 172-meter (565-foot) main stack based on average flow rates and in-stack SO_2 concentration measurements agree, within a few percent, with the amount required to achieve a sulfur balance. It follows that average SO_2 low-level fugitive emissions are quite small compared to the average SO_2 emissions discharged from the main stack. This conclusion is supported by comparisons of calculated annual average SO_2 concentrations for 1972 with observed air quality at SO_2 monitoring

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sites located in the Tacoma area. The best agreement between the calculated and observed concentrations is obtained when the average annual low-level fugitive emissions are effectively set to zero. During normal smelter operations, low-level fugitive emissions occur intermittently during loading, unloading and transfer of the concentrate as well as during the rolling of the converters. Also, for the existing 51-percent control smelter configuration, other fugitive emissions occur whenever the liquid SO_2 plant is down. Stations of the existing SO_2 monitoring network are too far away from the smelter to detect the effects of low-level fugitive emissions. It is possible, however, that fugitive emissions may account for the high SO_2 concentrations measured in Tacoma by the EPA mobile SO_2 monitor (see Appendix D) which was located approximately 1.2 kilometers from the main stack.

2.1 STACK PARAMETERS AND SO_2 EMISSION RATES FOR 17- and 51-PERCENT CONTROL

Basic stack parameter values and SO_2 emissions data for smelter operations at full production are listed in Table 2-1 for both 17- and 51-percent constant emissions control. As mentioned above, the stack and emissions data for 17-percent control were obtained from ASARCO and the latter are principally based on sulfur balance calculations. Although the emissions data are the best estimates available and appear to be accurate long-term averages, it is not possible to fix the magnitude of short-term (hourly, daily and weekly) variations that may have occurred. In addition to the SO_2 emissions from the main stack, small amounts of SO_2 were emitted from the acid plant and anode furnace stacks for the 17-percent control configuration. These emissions were on the order of 0.1 percent of the maximum uncurtailed emission rate for the main stack and thus had a minimal impact at the distances of the SO_2 monitors. Consequently, in our short-term and long-term historical calculations for the ASARCO smelter, we did not include the acid plant stack (17-percent control) or the anode furnace stack (17- and 51-percent control).

TABLE 2-1

ASARCO MAIN STACK PARAMETERS AND SO_2 EMISSIONS DATA FOR 17- AND 51-PERCENT CONSTANT EMISSIONS CONTROL AT FULL PRODUCTION

Parameter Values	Constant Emissions Control (Percent)	
	17 Percent	51 Percent
Stack Height (ft)	565	565
Elevation of Stack Base Above Mean Sea Level (ft)	150	150
Inner Stack Diameter (ft)	24	24
UTM Coordinates (m)		
X	537,370	537,370
Y	5,238,080	5,238,080
Volumetric Emission Rate (acfm)		
No Stack Heaters	524,769	553,000
One Stack Heater	587,482	553,000
Two Stack Heaters	636,237	553,000
Stack Exit Temperature (°F)		
No Stack Heaters	180	163
One Stack Heater	240	225
Two Stack Heaters	280	260
Maximum Uncurtailed SO_2 Emission Rate (lb/hr)	52,000	30,000

In the spring of 1974, ASARCO added a liquid SO_2 plant that increased the level of constant emissions control to 51 percent. SO_2 emissions from the pre-existing acid plant as well as the new liquid SO_2 plant were ducted to the main stack, thus eliminating the acid plant stack as a source. To assist in establishing representative values for the main stack parameters and SO_2 emission rates for the 51-percent control configuration, ASARCO provided detailed records of plant operations, in-stack SO_2 measurements, stack temperatures and flow rates for a 30-day period in the fall of 1975. These data were used to develop the parameters values and SO_2 emission rate for 51-percent control shown in Table 2-1. Additionally, a detailed analysis was made of the hourly data for twelve of the 30 days during which the smelter operations covered a broad range of production levels. This analysis showed that the actual volumetric emission rate from the main stack was unaffected in any systematic way by the number of stack heaters in operation and was therefore effectively constant. A second result of this detailed analysis of hourly data is presented in Figure 2-1 which shows a scatter diagram and a fitted linear least-squares regression curve relating measured in-stack SO_2 concentrations to SO_2 emission rates. The upper and lower curves in the figure are calculated 95-percent confidence limits. The relationship between the SO_2 emission rate Q in tons per hour and the measured in-stack SO_2 concentration ρ in parts per million (ppm) given by the least-squares regression curve is

$$Q\,(\text{tons/hr}) = 0.0028\,\rho\,(\text{ppm}) - 0.1165 \qquad (2\text{-}1)$$

The calculated linear correlation coefficient is 0.922 and the number of paired data points used in the calculation is 283. According to the confidence limits shown in Figure 2-1, there is a 95-percent probability that the actual SO_2 emission rate is within ± 20 percent of the rate calculated from Equation (2-1) using the measured in-stack SO_2 concentration. This equation was used to estimate the hourly SO_2 emission rates for three historical cases (18, 19, and 20) that occurred after the installation of the liquid SO_2 plant (see Section 4.3).

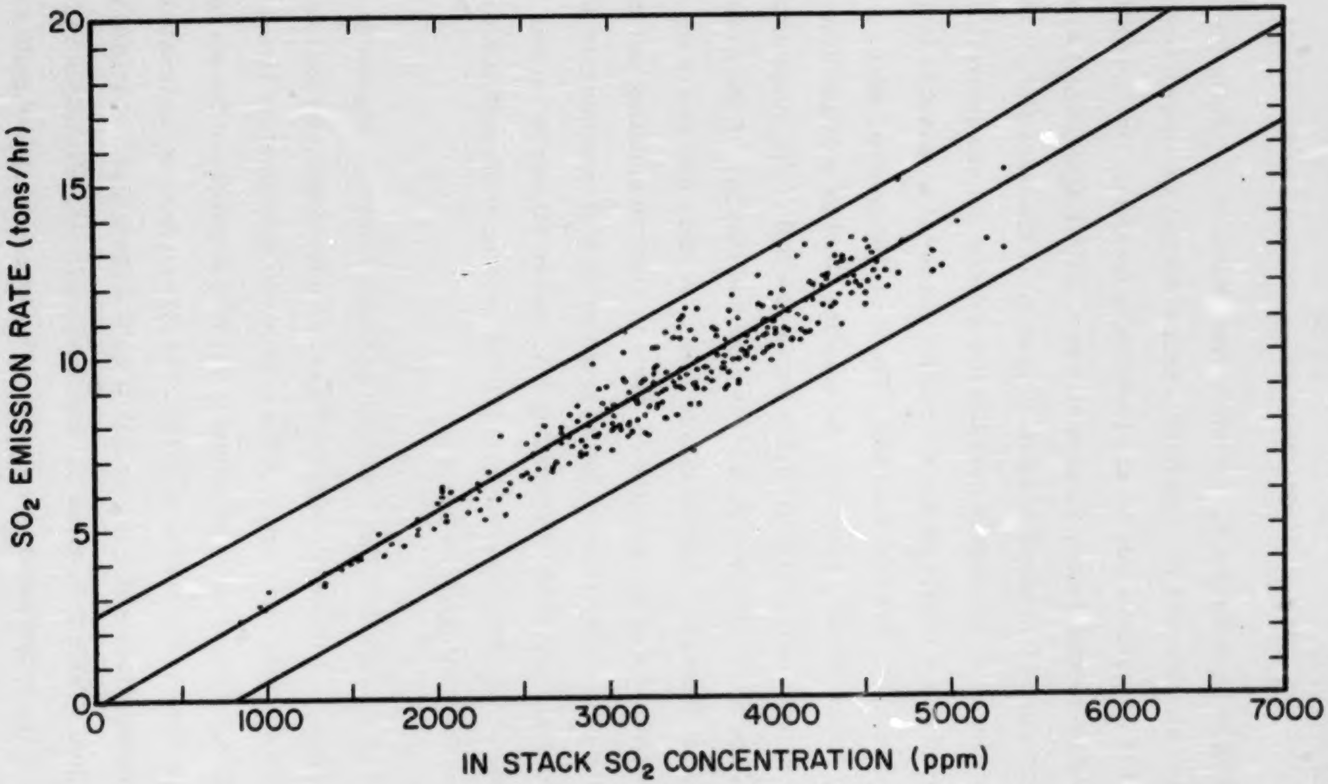

FIGURE 2-1. Scatter diagram of in-stack SO_2 concentration measurements versus SO_2 emission rates. Line drawn through the data points is the least-squares regression line while the upper and lower lines show the 97.5 and 2.5 percent confidence limits.

2.2 STACK PARAMETERS AND SO_2 EMISSIONS DATA FOR POSSIBLE FUTURE PLANT CONFIGURATIONS (CONTROL ALTERNATIVES)

According to EPA Region X, a study of the control of SO_2 from the ASARCO smelter indicates that two levels of constant emissions control beyond the current level of 51-percent control are technically feasible. By controlling either the roaster or reverberatory furnace streams, EPA Region X believes the sulfur capture can be increased to about 70 percent of the input sulfur. Sulfur removal on the order of 90 percent is possible if both streams are controlled. EPA Region X requested that we evaluate the air quality impact of 21 possible future plant configurations of the ASARCO smelter. These configurations, which are termed "Control Alternatives", start with the existing smelter configuration and cover a broad spectrum of methods available for the control of SO_2 emissions from the smelter. At one end of the spectrum, it is assumed that part of the roaster stream is controlled through an upgraded acid plant. At the other end of the spectrum, it is assumed that the smelter converts to electric smelting and uses a new, larger acid plant. It is assumed that degrees of control intermediate between these two extremes are achieved by upgrading SO_2 concentrations in various streams by means of SO_2 injection and by using the existing acid plant and/or a new acid plant for the final control devices.

Tables 2-2 through 2-13 list the stack and emissions data for the 21 Control Alternatives. The percent constant SO_2 emissions control as well as the types of emissions controls and details of the source configuration are listed at the top of each table. Source numbers given in the tables reference the source identification code used in the computer printout sheets containing the detailed diffusion-model calculations which are on file at EPA Region X and at PSAPCA in Seattle, Washington. Table 2-14 gives the assumed locations, elevations and source numbers of the hypothetical new stacks. The hypothetical new main stack is situated 70 meters (230 feet) west of the existing main stack. The other hypothetical stacks are located within the plant production area.

In our calculations for the existing plant configuration (Control Alternative 1), we used the average volumetric and uncurtailed SO_2 emission rates for 51-percent control given in Table 2-2; the SO_2 emission rate given in Table 2-1 is the maximum uncurtailed rate. Also, we used the stack exit temperature for no stack heaters in operation because the stack heaters are considered to be a part of the smelter's Supplementary Control System (SCS). Because the Froude number for the existing ASARCO stack is less than 3, the minimum value for which exit-velocity (downwash) restrictions on plume rise are believed to apply, no exit-velocity restrictions on plume rise were assumed in the calculations for this stack (see Appendix D).

It is important to note that the ASARCO smelter has apparently been unable to achieve the 51-percent constant emissions control called for in Control Alternative 1 (the existing plant configuration). According to EPA Region X and PSAPCA, the average SO_2 recovery is less than 45 percent because the existing emissions control equipment often operates below design efficiency.

TABLE 2-2

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVE 1

51 Percent Control Using Existing Emissions Controls and Existing Source Configuration without SCS.	
Existing Main Stack (Source #1001)	
Height (ft)	565
Exit Diameter (ft)	24
Average Flow Rate (acfm)	549,000
Minimum Flow Rate (acfm)	415,400
Maximum Flow Rate (acfm)	692,900
Exit Temperature (^{o}F)	
No Heaters	163
One Heater	225
Two Heaters	260
SO_2 Emission Rate (lb/hr)	24,802

TABLE 2-3

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVE 2

51 Percent Control Using Existing Emissions Controls, Existing Main Stack for Roasters and Reverbs with New Liquid SO_2 Plant Stack and New Acid Plant Stack.	
Acid Plant Stack (Source #1002)	
Height (ft)	100
Exit Diameter (ft)	2.5
Flow Rate (acfm)	26,508
SO_2 Emission Rate (lb/hr)	483
Exit Temperature (°F)	170
Liquid SO_2 Plant Stack (Source #1003)	
Height (ft)	100
Exit Diameter (ft)	3.0
Flow Rate (acfm)	51,945
SO_2 Emission Rate (lb/hr)	1,250
Exit Temperature (°F)	170
Existing Main Stack (Source #1004)	
Height (ft)	565
Exit Diameter (ft)	24.0
Flow Rate (acfm)	452,118
SO_2 Emission Rate (lb/hr)	23,070
Exit Temperature (°F)	150

TABLE 2-4

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVES 3 AND 4

Control Alternative 3--51 Percent Control Using New Main Stack, Existing Emissions Controls and Modifications Outlined in ASARCO Variance Application.	
New Main Stack (Source #1005)	
Height (ft)	500
Exit Diameter (ft)	12
Flow Rate (acfm)	516,546
SO_2 Emission Rate (lb/hr)	24,802
Exit Temperature (^oF)	170

Control Alternative 4--71 Percent Control Using Existing Main Stack, Existing Emissions Controls on Reverbs and Converters, New Acid Plant on Roasters after Enrichment by SO_2 Injection and Using Modifications Outlined in ASARCO Variance Application.	
Existing Main Stack (Source #1006)	
Height (ft)	565
Exit Diameter (ft)	24
Flow Rate (acfm)	400,288
SO_2 Emission Rate (lb/hr)	14,490
Exit Temperature (^oF)	170

TABLE 2-5

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVES 5 AND 6

Control Alternative 5--72 Percent Control Using Existing Main Stack, Existing Emissions Controls on Reverbs and Converters, Scrubber on Roasters and Using Modifications Outlined in ASARCO Variance Application.	
Existing Main Stack (Source #1007)	
Height (ft)	565
Exit Diameter (ft)	24
Flow Rate (acfm)	388,443
SO_2 Emission Rate (lb/hr)	14,250
Exit Temperature (^oF)	150

Control Alternative 6--72 Percent Control Using New Main Stack, Existing Emissions Controls on Reverbs and Converters, Scrubber on Roasters and Using Modifications Outlined in ASARCO Variance Application.	
New Main Stack (Source #1008)	
Height (ft)	500
Exit Diameter (ft)	12
Flow Rate (acfm)	388,443
SO_2 Emission Rate (lb/hr)	14,250
Exit Temperature (^oF)	150

TABLE 2-6

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVES 7 AND 8

Control Alternative 7--96 Percent Control Using Existing Main Stack, Electric Arc Furnace, Acid Plant on Roasters and Part of Converter Stream after Enrichment by SO_2 Injection, Liquid SO_2 Plant on Remainder of Converter Stream and Modifications Outlined in ASARCO Variance Application.	
Existing Main Stack (Source #1009)	
Height (ft)	565
Exit Diameter (ft)	24
Flow Rate (acfm)	344, 592
SO_2 Emission Rate (lb/hr)	1,900
Exit Temperature (°F)	150

Control Alternative 8--96 Percent Control Using New Main Stack, Electric Arc Furnace, Acid Plant on Roasters and Part of Converter Stream after Enrichment by SO_2 Injection, Liquid SO_2 Plant on Remainder of Converter Stream and Modifications Outlined in ASARCO Variance Application.	
New Main Stack (Source #1010)	
Height (ft)	500
Exit Diameter (ft)	8
Flow Rate (acfm)	344, 592
SO_2 Emission Rate (lb/hr)	1,900
Exit Temperature (°F)	150

TABLE 2-7

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVES 9 AND 10

Control Alternative 9--96 Percent Control Using Existing Main Stack, Existing Source Configuration, Scrubber on Roaster and Reverb Streams and with Modifications Outlined in ASARCO Variance Application.	
Existing Main Stack (Source #1011)	
Height (ft)	565
Exit Diameter (ft)	24
Flow Rate (acfm)	385,842
SO_2 Emission Rate (lb/hr)	2,240
Exit Temperature (^oF)	150

Control Alternative 10--96 Percent Control Using New Main Stack with Existing Source Configuration, Scrubber on Roaster and Reverb Streams and with Modifications Outlined in ASARCO Variance Application.	
New Main Stack (Source #1012)	
Height (ft)	500
Exit Diameter (ft)	10.5
Flow Rate (acfm)	385,842
SO_2 Emission Rate (lb/hr)	2,240
Exit Temperature (^oF)	150

TABLE 2-8

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVES 11 AND 12

Control Alternative 11--51 Percent Control Using Existing Main Stack, Existing Source Configuration and Existing Emissions Controls with Modifications Outlined in ASARCO Variance Application.	
Existing Main Stack (Source #1013)	
Height (ft)	565
Exit Diameter (ft)	24
Flow Rate (acfm)	402,962
SO_2 Emission Rate (lb/hr)	24,750
Exit Temperature (^{o}F)	170

Control Alternative 12--51 Percent Control Using New Main Stack, Existing Source Configuration and Existing Emissions Controls with Modifications Outlined in ASARCO Variance Application.	
New Main Stack (Source #1014)	
Height (ft)	500
Exit Diameter (ft)	10
Flow Rate (acfm)	402,962
SO_2 Emission Rate (lb/hr)	24,750
Exit Temperature (^{o}F)	170

TABLE 2-9

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVES 13 AND 14

Control Alternative 13--55 Percent Control Using Existing Main Stack, Existing Emissions Controls with 20 Percent of Roaster Stream through Existing Acid Plant after Enrichment by SO_2 Injection and with Modifications Outlined in ASARCO Variance Application.	
Existing Main Stack (Source #1015)	
Height (ft)	565
Exit Diameter (ft)	24
Flow Rate (acfm)	401,607
SO_2 Emission Rate (lb/hr)	22,840
Exit Temperature (°F)	170

Control Alternative 14--55 Percent Control Using New Main Stack, Existing Emissions Controls with 20 Percent of Roaster Stream through Existing Acid Plant after Enrichment by SO_2 Injection and with Modifications Outlined in ASARCO Variance Application.	
New Main Stack (Source #1016)	
Height (ft)	500
Exit Diameter (ft)	10
Flow Rate (acfm)	401,607
SO_2 Emission Rate (lb/hr)	22,840
Exit Temperature (°F)	170

TABLE 2-10

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVES 15 AND 16

Control Alternative 15--61 Percent Control Using Existing Main Stack with Liquid SO_2 Plant on Part of Converter Stream, New Acid Plant on 50 Percent of Roaster Stream after Enrichment by SO_2 Injection and with Modifications Outlined in ASARCO Variance	
Existing Main Stack (Source #1017)	
Height (ft)	565
Exit Diameter (ft)	24
Flow Rate (acfm)	400,846
SO_2 Emission Rate (lb/hr)	19,750
Exit Temperature (°F)	170

Control Alternative 16--61 Percent Control Using New Main Stack with Liquid SO_2 Plant on Part of Converter Stream, New Acid Plant on 50 Percent of Roaster Stream after Enrichment by SO_2 Injection and with Modifications Outlined in ASARCO Variance Application.	
New Main Stack (Source #1018)	
Height (ft)	500
Exit Diameter (ft)	10
Flow Rate (acfm)	400,846
SO_2 Emission Rate (lb/hr)	19,750
Exit Temperature (°F)	170

TABLE 2-11

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVES 17 AND 18

Control Alternative 17--72 Percent Control Using Existing Main Stack with Liquid SO_2 Plant on Part of Converter Stream, New Acid Plant on Remainder of Converter Stream and on 100 Percent of Roaster Stream after Enrichment by SO_2 Injection and Using Modifications Outlined in ASARCO Variance Application.	
Existing Main Stack (Source #1019)	
Height (ft)	**565**
Exit Diameter (ft)	**24**
Flow Rate (acfm)	**399,503**
SO_2 Emission Rate (lb/hr)	**14,160**
Exit Temperature (^oF)	**170**

Control Alternative 18--75 Percent Control Using Existing Main Stack with Existing Emissions Controls on Converter Stream and New Acid Plant on Reverb Stream after Enrichment by SO_2 Injection.	
New Main Stack (Source #1020)	
Height (ft)	**565**
Exit Diameter (ft)	**24**
Flow Rate (acfm)	**400,205**
SO_2 Emission Rate (lb/hr)	**12,730**
Exit Temperature (^oF)	**170**

TABLE 2-12

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVES 19 AND 20

Control Alternative 19--76 Percent Control Using Existing Main Stack with Liquid SO_2 Plant on Part of Converter Stream and New Acid Plant on Remainder of Converter Stream and on Reverb Stream after Enrichment by SO_2 Injection.	
Existing Main Stack (Source #1021)	
Height (ft)	565
Exit Diameter (ft)	24
Flow Rate (acfm)	399,277
SO_2 Emission Rate (lb/hr)	12,400
Exit Temperature (^oF)	170

Control Alternative 20--95 Percent Control Using Existing Main Stack with Existing Emissions Controls on Converter Stream and with New Acid Plant on Roaster and Reverb Streams after Enrichment by SO_2 Injection.	
New Main Stack (Source #1022)	
Height (ft)	565
Exit Diameter (ft)	24
Flow Rate (acfm)	385,693
SO_2 Emission Rate (lb/hr)	2,470
Exit Temperature (^oF)	150

TABLE 2-13

STACK AND EMISSIONS DATA FOR CONTROL ALTERNATIVE 21

Control Alternative 21--96 Percent Control Using Existing Main Stack, Existing Emissions Controls on Converter Stream, Electric Arc Furnace with New Acid Plant on Combined Furnace and Roaster Streams after Enrichment by SO_2 Injection.	
Existing Main Stack (Source #1023)	
Height (ft)	565
Exit Diameter (ft)	24
Flow Rate (acfm)	345,283
SO_2 Emission Rate (lb/hr)	2,230
Exit Temperature (^oF)	150

TABLE 2-14

ASSUMED LOCATIONS AND ELEVATIONS OF HYPOTHETICAL NEW ASARCO STACKS

Source Name	Source No.	Location		Elevation (ft above MSL)
		UTM X (m)	UTM Y (m)	
New Main Stack	1005, 1008 1010, 1012 1014, 1016 and 1018	537,300	5,238,080	121
Acid Plant Stack	1002	537,400	5,238,400	30
SO_2 Plant Stack	1003	537,500	5,238,400	33

SECTION 3

METEOROLOGICAL DATA

3.1 METEOROLOGY OF THE SEATTLE-TACOMA AREA

The meteorology of the Seattle-Tacoma area reflects the complex topography and the large number of land-water interfaces. Seattle and Tacoma are situated on the eastern shore of Puget Sound, which has an approximate north-south orientation. To the west of Puget Sound, the Olympic Mountain Range effectively shields the entire area from west winds. Terrain elevations in the immediate Seattle-Tacoma area range from sea level to 150 meters above sea level. Additionally, the land surface varies from relatively smooth tidal flats and beaches to rugged hills. These variations in terrain height, type and orientation significantly affect the wind flow. Variations in wind speed, wind direction and atmospheric stability indicated by an analysis of meteorological measurements at four locations in the Seattle-Tacoma area are described below.

Wind-Direction Distributions

Figure 3-1 shows the 1972 annual frequency distributions of wind direction at the N26th and Pearl station in Tacoma (solid line) and at McChord Air Force Base (dashed line). The directions in Figure 3-1 have been reversed 180 degrees to show the directions toward which the wind is blowing and thus the effects of wind direction on the areal distribution of pollutants. The N26th and Pearl station is approximately 3 kilometers south of the stack of the ASARCO smelter, and McChord AFB is about 18 kilometers south of the stack. The two wind-direction distributions are similar and indicate a general north-south circulation in the Tacoma area. As shown by Figure 3-1, the wind-direction distributions at the two sites would be nearly identical if the McChord wind directions were rotated 22.5 degrees clockwise. We believe this difference is due to differences in the orientation of Puget Sound.

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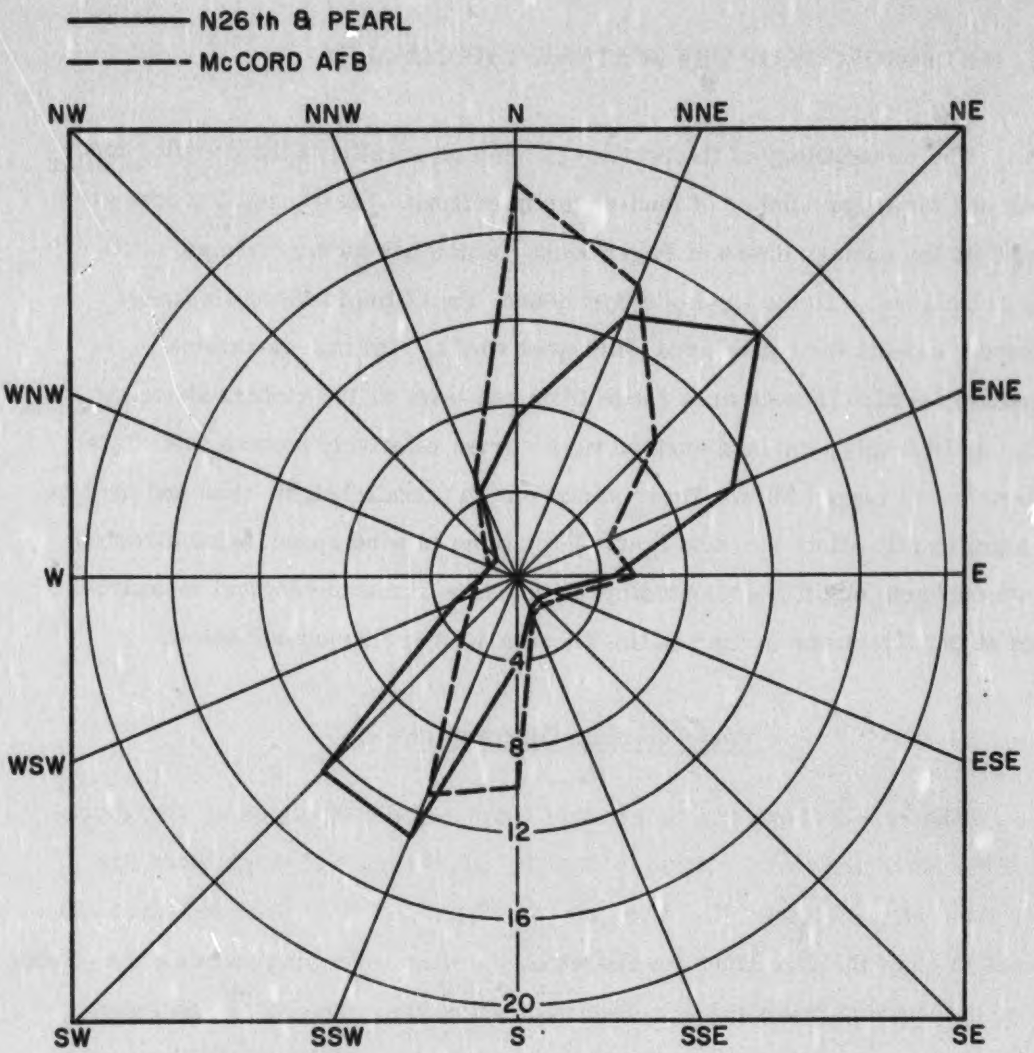

FIGURE 3-1. 1972 annual frequency distributions of wind direction at N26th and Pearl (solid line) and McChord Air Force Base (dashed line). The directions are directions toward which the wind is blowing and the percentage frequency scale is shown in the lower half of the figure.

Figure 3-2 shows the 1972 annual frequency distributions of wind direction at the Seattle-Tacoma Airport (solid line) and at Boeing Field (dashed line). The directions in Figure 3-2 are also directions toward which the wind is blowing. The Seattle-Tacoma Airport is located about 23 kilometers northeast of the ASARCO stack while Boeing Field is located about 30 kilometers north-northeast of the stack. The wind-direction distribution at the Seattle-Tacoma Airport is similar to the distributions at McChord AFB and the N26th and Pearl station. The wind-direction distribution for Boeing Field appears invalid because of the low frequency of occurrence of north and south winds as compared to the high frequency of occurrence of north-northwest, north-northeast, south-southeast and south-southwest winds. However, the possibility of errors in the Boeing Field wind-direction data does not affect the results of this study.

Wind-Speed Distributions

Table 3-1 lists the 1972 annual frequency distributions of wind speed at N26th and Pearl, McChord AFB, the Seattle-Tacoma Airport and Boeing Field. As shown by the table, the wind-speed distributions at McChord AFB and N26th and Pearl are essentially the same; also, the wind-speed distributions at the Seattle-Tacoma Airport and Boeing Field are nearly identical. However, the wind-speed distributions for N26th and Pearl and McChord AFB differ significantly from the wind-speed distributions for the Seattle-Tacoma Airport and Boeing Field. Specifically, very light surface winds (wind speeds less than about 1.5 meters per second) occur about four times more frequently in the Tacoma area than in the Seattle area.

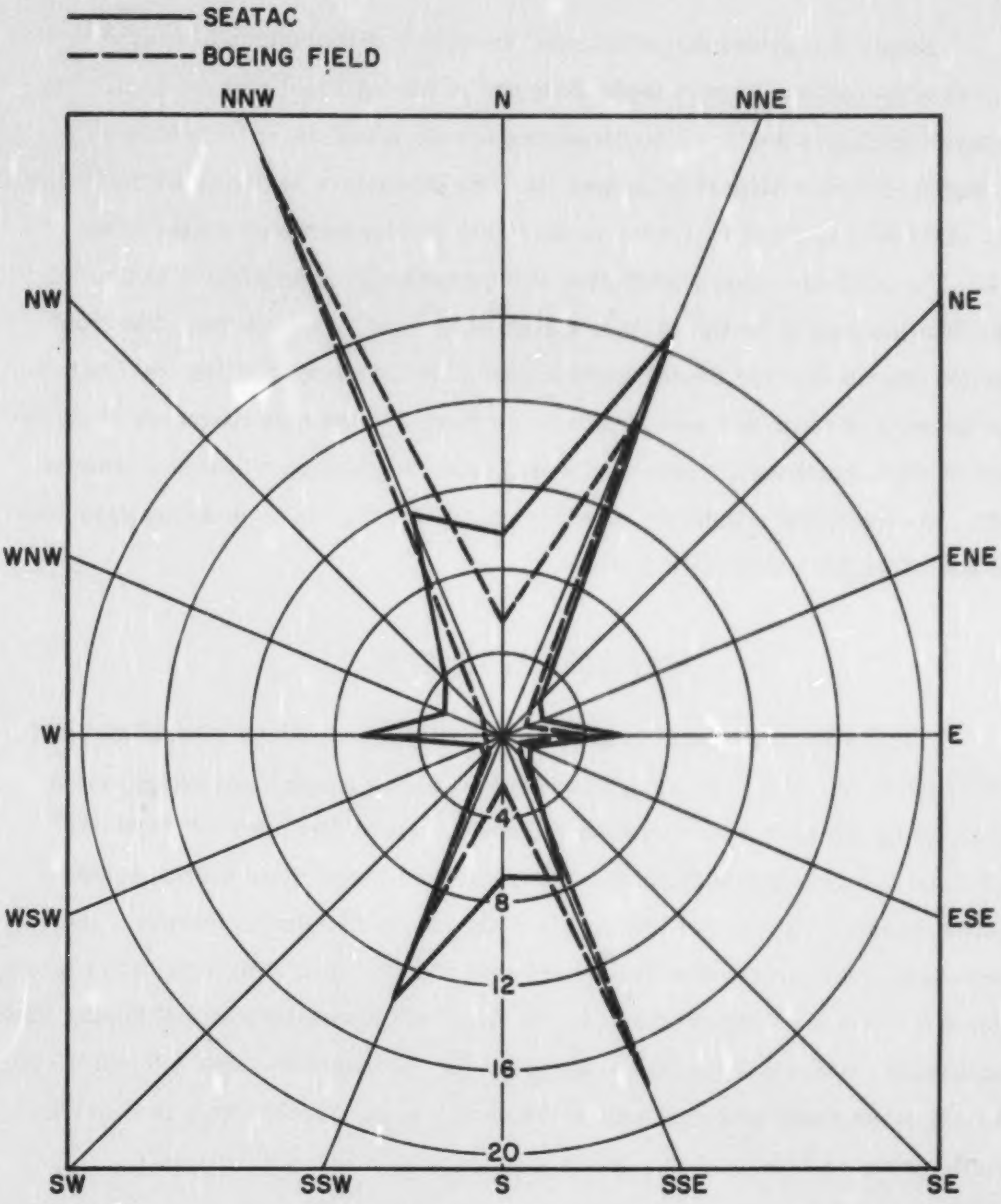

FIGURE 3-2. 1972 annual frequency distributions of wind direction at the Seattle-Tacoma Airport (solid line) and Boeing Field (dashed line). The directions are the directions toward which the wind is blowing and the percentage frequency scale is shown in the lower half of the figure.

TABLE 3-1

1972 ANNUAL WIND-SPEED DISTRIBUTIONS AT N26th AND PEARL, MC CHORD AIR FORCE BASE, SEATTLE-TACOMA AIRPORT (SEATAC) AND BOEING FIELD

Wind Speed (m/sec)	Annual Percent Frequency of Occurrence			
	N26th and Pearl	McChord AFB	SEATAC	Boeing Field
0 - 1.5	35.63	33.89	6.75	9.99
1.6 - 3.0	29.94	33.80	41.96	40.68
3.1 - 5.1	21.05	17.65	31.96	31.98
5.2 - 8.2	11.64	13.13	16.97	16.42
8.3 - 10.8	1.54	1.17	2.18	0.85
>10.8	0.20	0.36	0.18	0.08

Stability Distributions

Turner (1964) has developed a procedure to determine the Pasquill stability category on the basis of airport surface weather observations. The Turner definitions of the Pasquill stability categories are based on solar radiation (insolation), as estimated from cloud cover and time of day, and wind speed. Tables 3-2 and 3-3 list the parameters that define the various stability categories. The thermal stratifications represented by the six stability categories are:

- A - Very unstable
- B - Unstable
- C - Slightly unstable
- D - Neutral
- E - Stable
- F - Very stable

Table 3-4 lists the 1972 annual frequency distributions of the Pasquill stability categories at N26th and Pearl, McChord AFB, Seattle-Tacoma Airport and Boeing Field. Because no cloud cover observations were available for N26th and Pearl, cloud cover observations at McChord AFB were used in conjunction with concurrent wind measurements at N26th and Pearl to determine the stability categories at N26th and Pearl. The stability distributions at McChord AFB and N26th and Pearl are essentially the same and the stability distributions at the Seattle-Tacoma Airport and Boeing Field are very similar. However, unstable and very stable conditions are more frequent at the Tacoma area sites (McChord AFB and N26th and Pearl) than at the Seattle area sites (Seattle-Tacoma Airport and Boeing Field). The higher frequency of occurrence of light winds in the

TABLE 3-2

PASQUILL STABILITY CATEGORY AS A FUNCTION OF INSOLATION AND WIND SPEED

Wind Speed (knots)	Insolation Index						
	4	3	2	1	0	-1	-2
0, 1	A	A	B	C	D	F	F
2, 3	A	B	B	C	D	F	F
4, 5	A	B	C	D	D	E	F
6	B	B	C	D	D	E	F
7	B	B	C	D	D	D	E
8, 9	B	C	C	D	D	D	E
10	C	C	D	D	D	D	E
11	C	C	D	D	D	D	D
≥ 12	C	D	D	D	D	D	D

TABLE 3-3

INSOLATION CATEGORIES

Insolation	Insolation Category Number
Strong	4
Moderate	3
Slight	2
Weak	1
Overcast < 7000 feet (day or night)	0
Cloud Cover > 4/10 (night)	-1
Cloud Cover ≤ 4/10 (night)	-2

Tacoma area (see Table 3-1) is consistent with these differences in stabilities. As indicated by Tables 3-2 and 3-3, a higher frequency of light winds will result in a higher frequency of unstable and very stable conditions. It should be noted that all four sites in the Seattle-Tacoma area show that the neutral D stability category occurs more than half of the time.

The 1972 annual frequency distribution of wind-speed and wind-direction categories at N26th and Pearl, classified according to the Pasquill stability categories, is presented in Appendix B. We believe that, of the available wind data, the N26th and Pearl data are the most representative of the winds that affect the transport and dispersion of emissions from the ASARCO smelter.

Wind Persistence

In order to assess the frequency of occurrence of maximum 3-hour and 24-hour ground-level concentrations, it is necessary to know the combined persistence of wind speed and wind direction for time periods up to 24 hours. Table 3-5 lists the total number of occurrences at N26th and Pearl during the period January through December 1972 of the persistence of wind directions and wind speeds greater than 5.1 meters per second for time periods from 1 to 24 hours. As shown by the table, the most persistent wind directions in the Tacoma area are north-northeast, east-northeast, south-southwest and west-southwest. The maximum persistence during 1972 of moderate to strong winds within a wind-direction sector was 20 hours for north-northeast winds.

Mixing Depths

We have analyzed tabulations of the seasonal frequency of occurrence of surface mixing depths measured at the Seattle-Tacoma Airport during the period

TABLE 3-4

1972 ANNUAL DISTRIBUTIONS OF THE PASQUILL STABILITY CATEGORIES AT N26th AND PEARL, MC CHORD AFB, THE SEATTLE-TACOMA AIRPORT AND BOEING FIELD

Pasquill Stability Category	Annual Percent Frequency of Occurrence			
	N26th and Pearl	McChord AFB	SEATAC	Boeing Field
A	0.42	0.80	0.18	0.10
B	6.91	9.81	4.87	4.34
C	9.89	10.96	9.96	9.81
D	53.94	55.66	61.46	60.46
E	7.93	5.67	13.15	11.54
F	20.91	17.10	10.39	13.74

TABLE 3-5

TOTAL NUMBER OF OCCURRENCES DURING 1972 OF THE PERSISTENCE OF WIND DIRECTION AND WIND SPEEDS GREATER THAN 5.1 METERS PER SECOND AT N26th AND PEARL

Number of Hours of Persistence	Wind Direction (Sector)															
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
≥ 1	22	165	74	16	7	1	2	4	77	301	266	179	14	0	0	1
≥ 2	6	66	25	8	2	0	1	2	27	109	88	62	5	0	0	0
≥ 3	3	31	11	4	1	0	0	0	11	53	38	28	1	0	0	0
≥ 4	2	21	7	3	0	0	0	0	7	31	22	18	1	0	0	0
≥ 5	1	14	2	2	0	0	0	0	3	19	12	11	0	0	0	0
≥ 6	0	9	0	3	0	0	0	0	3	11	5	7	0	0	0	0
≥ 7	0	6	0	3	0	0	0	0	2	7	3	4	0	0	0	0
≥ 8	0	5	0	1	0	0	0	0	2	4	2	3	0	0	0	0
≥																
≥ 9	0	4	0	1	0	0	0	0	1	3	1	3	0	0	0	0
≥ 10	0	3	0	1	0	0	0	0	0	2	1	3	0	0	0	0
≥ 11	0	2	0	1	0	0	0	0	0	1	0	2	0	0	0	0
≥ 12	0	2	0	1	0	0	0	0	0	1	0	2	0	0	0	0
≥ 13	0	2	0	1	0	0	0	0	0	1	0	1	0	0	0	0
≥ 14	0	2	0	1	0	0	0	0	0	1	0	1	0	0	0	0
≥ 15	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥ 16	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥ 17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥ 18	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥ 19	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥ 20	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥ 21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥ 22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥ 23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥ 24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1959 through 1961 (Environmental Data Service, 1967) in order to determine seasonal mixing depths for each time-of-day and wind-speed category. Table 3-6 lists the median early morning and afternoon mixing depths for each season. Although the early morning mixing depths calculated by the Environmental Data Service are assumed to apply at 0800 PST, we believe that they are representative of nighttime conditions in the Seattle-Tacoma area because of the effects of heat sources and surface roughness. Table 3-6 shows that the diurnal variation of the mixing depth is at a minimum in the winter and at a maximum in the spring and summer. For wind speeds less than 5.1 meters per second, mixing depths during the winter are quite shallow throughout the day.

3.2 CRITICAL METEOROLOGICAL REGIMES

Based on our review of meteorological, emissions and air quality data, we believe that there are three meteorological regimes in the Tacoma area that are conducive to high ground-level SO_2 concentrations produced by stack emissions from the ASARCO smelter. These critical regimes are:

- The critical wind-speed condition
- Fumigation
- The limited-mixing condition

The Critical Wind-Speed Condition

The critical wind-speed condition (neutral stability in combination with moderate to strong winds) is the most persistent of the three meteorological regimes and is thus the regime most likely to produce the highest ground-level SO_2 concentrations for averaging times of 3 and 24 hours. Because high ground-level concentrations produced by the critical wind-speed condition are generally confined

TABLE 3-6

MEDIAN MIXING DEPTHS MEASURED AT THE SEATTLE-TACOMA AIRPORT DURING THE PERIOD 1959 THROUGH 1961

Wind Speed (m/sec)	Median Mixing Depth (m)							
	Winter		Spring		Summer		Fall	
	Night	Afternoon	Night	Afternoon	Night	Afternoon	Night	Afternoon
0 - 1.5	125	375	125	1250	125	1250	125	625
1.6 - 3.0	125	375	375	1250	375	1250	125	875
3.1 - 5.1	375	375	675	1250	375	1250	375	875
5.2 - 8.2	625	625	875	1250	625	1250	875	875
8.3 - 10.8	625	625	1250	1250	1250	1250	875	875
>10.8	625	625	1250	1250	1250	1250	875	875

within a narrow angular sector, it is difficult to detect maximum ground-level concentrations that occur under this regime with a conventional air quality monitoring network because the requisite density of fixed monitoring stations is logistically infeasible.

Fumigation

When a stack plume is contained in a stable layer above the top of the surface mixing layer, the plume remains aloft and does not mix to the ground. Concentrations within the plume are high because of the very limited turbulent mixing. When the top of the surface mixing layer reaches the height of the stack plume, the pollutants are suddenly brought to the ground. This process, called fumigation, is transient and typically results in high ground level concentrations that rarely persist for longer than 1 or 2 hours. Turner (1969) assumes a narrow ribbon-like plume in the stable layer prior to fumigation. However, we found no evidence of the classical ribbon-like plume in the fumigation cases we studied. Instead of being confined in a narrow plume, the emissions at plume stabilization height appear to be spread over a wide angular sector that may be as large as 360 degrees prior to fumigation. Briggs (1965) describes a similar behavior for plumes from TVA power plants. We believe that daytime heating is generally the cause of the fumigation in the Tacoma area. An exception is one case of a nighttime fumigation (3 October 1972, see Section 4.3), possibly associated with vertical wind shear. We have not found any evidence of sea-breeze fumigation as described by Lyons and Cole (1973), probably because the land-water temperature difference in the Tacoma area is generally much less than the land-water difference for the cases studied by Lyons and Cole. Also, the over-water fetch of air reaching the Tacoma area is perhaps shorter than the over-water fetch associated with the usual sea-breeze fumigations.

The Limited-Mixing Condition

The most common critical meteorological regime, the limited-mixing condition, occurs with light winds whenever the ASARCO plume is contained within the surface mixing layer. It should be noted that this definition differs from the TVA definition of the limited-mixing condition (Carpenter, et al., 1971). We have used the term "limited mixing" because it most accurately characterizes the meteorological structure in the Tacoma area during these periods.

3.3 GENERAL METEOROLOGICAL INPUTS

The following procedures were used to specify the general meteorological inputs required by the short-term and long-term diffusion models described in Appendix A.

Vertical Turbulent Intensities

Our vertical expansion (σ_z) equation, which includes the effects of the initial vertical plume or building dimension, relates the vertical turbulent intensity directly to plume growth (see Equation (A-13) of Appendix A). Table 3-7 lists the values of the standard deviation of the wind elevation angle σ'_E corresponding to the Pasquill stability categories. These values are based in part on the measurements of Luna and Church (1971) and are consistent with the σ'_E values implicit in the vertical expansion curves presented by Pasquill (1961). In our calculations, we have combined the E and F stability categories because we believe that surface roughness elements and heat sources in the vicinity of the ASARCO smelter are incompatible with the small diffusion coefficients and minimal turbulent mixing associated with the Pasquill F stability category.

Lateral Turbulent Intensities

Our lateral expansion (σ_y) equation, which also includes the effects of the initial lateral plume or building dimension, relates the lateral turbulent intensity directly to plume growth (see Equation (A-11) of Appendix A). In our calculations, we assumed that the standard deviation of the wind azimuth angle σ'_A is equivalent to σ'_E for a 10-minute averaging period. This assumption is supported by bivane measurements made by Luna and Church (1971) and others at heights on the order of 100 meters above the surface. The $t^{1/5}$ law suggested by Osipov (1972) and others was then used to obtain hourly σ'_A values. That is, σ'_E for a given stability category was multiplied by 1.43 ($6^{1/5}$) to obtain the corresponding hourly σ'_A value. Table 3-7 also lists the σ'_A values used in our calculations.

Wind-Profile Exponents

In the diffusion models, the variation with height of the wind speed in the surface mixing layer is assumed to follow a wind-profile exponent law of the form

$$\bar{u}\{z\} = \bar{u}\{z_R\}\left(\frac{z}{z_R}\right)^p \tag{3-1}$$

where

$\bar{u}\{z\}$ = wind speed at height z above the surface
$\bar{u}\{z_R\}$ = wind speed at reference height z_R above the surface
p = the wind-profile exponent

The wind-profile exponent law is used to adjust the mean wind speed from the reference height (in this study, the measurement height at N26th and Pearl) to the stack height for the plume-rise calculations and to the plume stabilization height for the concentration calculations. Values of the wind-profile exponent p assigned to the various combinations of wind speed and stability for the short-term and long-term calculations are listed in Table 3-8. These exponent values are based on the results obtained by DeMarrais (1959) and Cramer, et al. (1972).

TABLE 3-7

VERTICAL AND LATERAL TURBULENT INTENSITIES

Pasquill Stability Category	σ_E' (rad)	σ_A' (rad)
A	0.1745	0.2495
B	0.1080	0.1544
C	0.0735	0.1051
D	0.0465	0.0665
E	0.0350	0.0501

TABLE 3-8

WIND PROFILE EXPONENTS

Pasquill Stability Category	Wind-Speed Category (meters per second)					
	0.0 - 1.5	1.6 - 3.1	3.2 - 5.1	5.2 - 8.2	8.3 - 10.8	>10.8
A	0.10	0.10	----	----	----	----
B	0.10	0.10	0.10	----	----	----
C	0.20	0.15	0.10	0.10	0.10	0.10
D	0.25	0.20	0.15	0.10	0.10	0.10
E	0.30	0.25	0.25	----	----	----

Mixing Depths

Table 3-9 lists the mixing depths assigned to the various combinations of wind-speed and stability categories. The mixing depths assigned to the unstable A, B and C stability categories are the average of the seasonal median afternoon mixing depths (see Table 3-6). Similarly, the mixing depths assigned to the combined E and F stability categories are the average of the median early morning mixing depths. The median early morning and afternoon mixing depths were averaged and assigned to the D stability category. The mixing depths in Table 3-9 were used in the long-term calculations. The mixing depths used in the short-term calculations were estimated from the concurrent upper-air sounding at the Portage Bay EMSU station closest to the time period of interest.

Ambient Air Temperatures

The Briggs (1971) plume-rise equations given in Section A. 2 of Appendix A require the ambient air temperature as an input. The ambient air temperatures used in the short-term calculations were the temperatures measured at McChord Air Force Base. The ambient air temperatures used in the long-term calculations are listed in Table 3-10. These ambient temperatures were determined by averaging the monthly average temperatures for Seattle, Washington which are published in the Climatic Atlas of the United States (1968). The normal daily maximum temperature was assigned to the A, B and C stability categories; the average daily temperature was assigned to the D stability category; and the normal daily minimum temperature was assigned to the combined E and F stability categories.

Vertical Potential Temperature Gradients

The Briggs (1971) plume-rise equations given in Section A. 2 of Appendix A also require the vertical potential temperature gradient as an input. Table 3-10 also lists the potential temperature gradients assigned to the various combinations

TABLE 3-9

MIXING DEPTHS IN METERS

Pasquill Stability Category	Wind-Speed Category (meters per second)					
	0.0 - 1.5	1.6 - 3.1	3.2 - 5.1	5.2 - 8.2	8.3 - 10.8	> 10.8
A	875	940	----	----	----	----
B	875	940	940	----	----	----
C	875	940	940	1000	1000	1000
D	500	595	690	875	1000	1000
E	125	250	440	----	----	----

TABLE 3-10

AMBIENT AIR TEMPERATURES AND VERTICAL POTENTIAL TEMPERATURE GRADIENTS

Pasquill Stability Category	Ambient Air Temperature (^oK)	Potential Temperature Gradient ($^oK/m$)					
		Wind-Speed Category (meters per second)					
		0.0-1.5	1.6-3.1	3.2-5.1	5.2-8.2	8.3-10.8	>10.8
A	288	0.00	0.00	----	----	----	----
B	288	0.00	0.00	----	----	----	----
C	288	0.00	0.00	0.00	0.00	0.00	0.00
D	284	0.00	0.00	0.00	0.00	0.00	0.00
E	279	0.03	0.02	0.01	----	----	----

of wind-speed and stability categories. The potential temperature gradients in Table 3-10 are based on the Turner (1964) and Pasquill (1961) definitions of the Pasquill stability categories, the measurements of Luna and Church (1971), and our own previous experience. The potential temperature gradients in Table 3-10 were used in the long-term calculations. The potential temperature gradients used in the short-term calculations were estimated from the concurrent upper-air sounding at the Portage Bay EMSU station.

SECTION 4

HISTORICAL CALCULATIONS

4.1 SELECTION OF DIFFUSION MODELS

During our background study of the ASARCO smelter, we reviewed a number of long-term and short-term atmospheric diffusion models that might be applicable to the topographical and meteorological factors affecting the dispersion of smelter SO_2 emissions. On the basis of our survey, we selected one long-term and five short-term models that were tested during the Model Development Phase of our study. The long-term model was the H. E. Cramer Company generalized long-term diffusion model (Cramer, et al., 1975). As noted in Section A.4 of Appendix A, this model is very similar to the EPA's Climatological Dispersion Model (CDM). The results of our calculations using the long-term model are discussed in detail in Section 4.2. The short-term models that we tested were:

- The H. E. Cramer Company short-term model (Cramer, et al., 1975)
- The Lyons and Cole (1973) sea-breeze fumigation model
- The Turner (1969) fumigation model
- The H. E. Cramer Company air-stagnation model (Cramer and Bowers, 1974)
- The Briggs (1965) air-stagnation model

With the exception of the H. E. Cramer Company short-term and long-term models, it was necessary to modify all of the above models to include the effects of variations in terrain height over the calculation grid. The results of trial calculations using the five short-term models are briefly discussed in the following paragraphs.

The H. E. Cramer Company short-term model (see Section A. 3 of Appendix A) is a generalized model that accepts site-specific meteorological input parameters and includes terrain effects. We have used this model in a number of air quality impact studies (for example, Cramer, et al., 1975), and the correspondence between calculated and observed concentrations has generally been excellent. As discussed in detail in Section 4. 3, the model worked well in historical calculations for two of the three critical meteorological regimes: the critical wind-speed condition and the limited-mixing condition (see Section 3. 2).

In our analysis of the air quality and meteorological data, we found two hours (6 September and 7 October 1974) when sea-breeze fumigation may have resulted in high ground-level SO_2 concentrations in the Tacoma area. Sea-breeze fumigation is a process that can occur when the land is significantly warmer than an adjacent large body of water and a sea breeze transports a stable air mass that has formed above the water over the land. A new unstable boundary layer with a semi-parabolic shape then begins to form at the land-water interface. The plume from a stack located near the shoreline that stabilizes above the new (unstable) boundary layer will travel inland with minimal growth until it intersects the thermally-unstable boundary layer, where the plume is brought quickly to the ground. For the two hours when sea-breeze fumigation may have occurred, our short-term model matched the observed concentrations as well as, or better than, the Lyons and Cole (1973) sea-breeze fumigation model. As noted in Section 3. 2, we believe that the land-water temperature difference in the Tacoma area is generally too small for sea-breeze fumigation as described by Lyons and Cole to occur. Also, the over-water fetch in the Tacoma area may not be long enough to permit the formation of a deep stable layer.

We have found no evidence in the air quality data for the fumigation of a narrow, ribbon-like plume as described by Turner (1969). Instead of being confined in a narrow plume, the emissions at plume stabilization height appear to be spread over a wide angular sector that may be as large as 360 degrees prior to the fumigation. When fumigation begins, high ground-level SO_2 concentrations occur almost simultaneously over the entire area. Briggs (1965) describes a similar behavior for plumes from TVA power plants. However, the Briggs (1965) model overpredicted the observed concentrations by as much as a factor of 3 to 5. The Cramer and Bowers (1974) air-stagnation fumigation model tended to underestimate the maximum hourly concentrations, but generally agreed well with the average concentrations for the period of fumigation. The Cramer and Bowers model is a modification of the long-term diffusion model described in Section A.4 of Appendix A. The model makes the following assumptions:

- Plume rise is determined by the stable meteorological conditions prior to fumigation
- The wind-direction distribution in the stable layer is circular (i.e., pollutants in the stable layer are spread about the stack in a circular pattern)
- When the mixing depth reaches the plume stabilization height, the pollutants are rapidly mixed to the ground (the rate of vertical mixing is determined by the vertical turbulent intensity in the unstable surface layer)

Based on the trial calculations using the five short-term models described above, we selected two models for use in the short-term historical calculations which are summarized in Section 4.3 and described in detail in Appendix E. The H. E. Cramer Company generalized short-term model was used for all short-term historical cases except the fumigation cases; the H. E. Cramer Company air-stagnation fumigation model was used for the fumigation cases.

It should be noted that the short-term diffusion models that we selected for use in this study are advanced forms of the Gaussian plume model and thus are very similar to the models used by EPA and others. However, the principal advantage of the selected models is that they use meteorological inputs that can be directly related to observed meteorological conditions and also include the most recent developments in the treatment of buoyant plume rise as well as variations in terrain height.

4.2 1972 ANNUAL AVERAGE CONCENTRATION CALCULATIONS

Variations in stack exit temperatures, flow rates and SO_2 emissions resulting from the operation of the ASARCO SCS complicated the selection of ASARCO source input parameters used in modeling the 1972 annual average concentrations. Analysis of the 1972 curtailment reports submitted by ASARCO to PSAPCA showed that the two stack heaters were generally turned on during the daytime and at such other times when high SO_2 ground-level concentrations were either observed or expected to occur at the monitors. Similarly, the 1972 curtailment reports indicated that smelter SO_2 emissions were routinely curtailed 50 to 90 percent or more when both stack heaters were turned on. We interpret this to mean that, whenever the plume from the main stack was observed or expected to be in the surface mixing layer (which is the required condition for high ground-level concentrations at the monitors impacted by the ASARCO plume), operation of the SCS resulted in both stack heaters being turned on and emissions curtailments of 50 to 90 percent.

To take into account the effects of the ASARCO SCS on SO_2 emissions during 1972, a hypothetical SCS operating regime was developed for the 1972 annual concentration calculations. Any such approximation of the SCS operating regime must be consistent with the curtailment reports and the total SO_2 emissions during 1972. In our hypothetical SCS operating regime, the following assumptions were made:

- The exit temperature and volumetric emission rate given in Table 2-1 for the main ASARCO stack with both heaters in operation applied whenever the ASARCO plume was contained within the surface mixing layer

- On the average, the smelter SCS reduced SO_2 emissions on the basis of wind speed and the Pasquill stability category as shown in Table 4-1

- As shown in Table 4-2, the SO_2 emission rate for each joint combination of wind-speed and stability categories was obtained from the product of the maximum uncurtailed emission rate for 17-percent permanent control (26 tons per hour) and the percent emissions reduction given in Table 4-1

If the hourly emission rate given in Table 4-2 for each wind-speed/stability combination is multiplied by the number of hours during 1972 of that particualr wind-speed/stability combination (see Appendix B) and the annual emissions thus obtained for each combination are summed, the calculated total SO_2 emissions from the main ASARCO stack during 1972 are 155,562 tons. This is very close to the total annual emissions for 1972 of 156,000 tons reported by ASARCO. Thus, our hypothetical SCS operating regime is consistent with both the curtailment reports and the total emissions reported by ASARCO for 1972. However, we recognize that this hypothetical SCS operating regime for 1972 is only one of a number of possible regimes.

The general meteorological inputs discussed in Section 3.3, the annual wind distributions at N26th and Pearl given in Appendix B, the ASARCO emissions data discussed above and the emissions data for the other sources in the Seattle-Tacoma area listed in Appendix C were used with the long-term concentration

TABLE 4-1

PERCENT REDUCTION IN SO_2 EMISSIONS ASSUMED IN THE 1972 ANNUAL CONCENTRATION CALCULATIONS

Pasquill Stability Category	Wind Speed (m/sec)					
	0.0 - 1.5	1.6 - 3.0	3.1 - 5.1	5.2 - 8.2	8.3 - 10.8	≥10.8
A	90	90	--	--	--	--
B	90	90	90	--	--	--
C	80	80	80	80	80	--
D	0	0	60	60	60	60
E	0	0	50	--	--	--
F	0	0	--	--	--	--

TABLE 4-2

SO_2 EMISSION RATES IN TONS PER HOUR ASSUMED IN THE 1972 ANNUAL CONCENTRATION CALCULATIONS

Pasquill Stability Category	Wind Speed (m/sec)					
	0.0 - 1.5	1.6 - 3.0	3.1 - 5.1	5.2 - 8.2	8.3 - 10.8	≥10.8
A	2.6	2.6	---	---	---	---
B	2.6	2.6	2.6	---	---	---
C	5.2	5.2	5.2	5.2	5.2	---
D	26.0	26.0	10.4	10.4	10.4	10.4
E	26.0	26.0	13.0	---	---	---
F	26.0	26.0	---	---	---	---

model described in Section A.4 of Appendix A to calculate 1972 annual average ground-level SO_2 concentrations. Kaiser Aluminum was not included in the calculations because SO_2 emissions were discharged from a 152-meter (500-foot) stack during 1972 and we do not know the exit parameters for this stack. Concentrations were calculated for a total of 1012 grid points on a 20-kilometer grid. The grid spacing within 6 kilometers of the ASARCO smelter was 0.5 kilometers; a 1-kilometer grid spacing was used beyond 6 kilometers. Concentrations were also calculated for the locations of the PSAPCA and ASARCO air quality monitors. The procedures described in Section A.5 of Appendix A were used to account for variations in terrain height over the calculation grid. Also, the SO_2 decay constant ψ (see Equations (A-9) and (A-23) in Appendix A) was set equal to zero because the rate of decay, although not well established, is believed to be insignificant for the distance and time intervals considered in this study (see Eliassen and Saltbones, 1975).

Figure 4-1 shows the calculated isopleths of annual average ground-level SO_2 concentration produced by the combined sources. The location of the main ASARCO stack is indicated by the star in the figure. The calculated maximum annual average SO_2 concentration of 0.0145 parts per million (ppm) is located about 6.5 kilometers southeast of the main ASARCO stack. The St. Regis Paper Mill is principally responsible for this calculated concentration; the contribution of ASARCO emissions is negligible at this point. The calculated concentration isopleths in Figure 4-1 indicate that the 1972 annual average SO_2 concentrations in the Tacoma area were below the National and PSAPCA ambient air quality standards of 0.03 and 0.02 ppm, respectively.

Figure 4-2 shows the calculated isopleths of annual average ground-level SO_2 concentration due to the ASARCO emissions. The isopleth pattern closely resembles the reversed wind-direction distribution at N26th and Pearl shown in Figure 3-1. The calculated maximum annual average concentration produced by

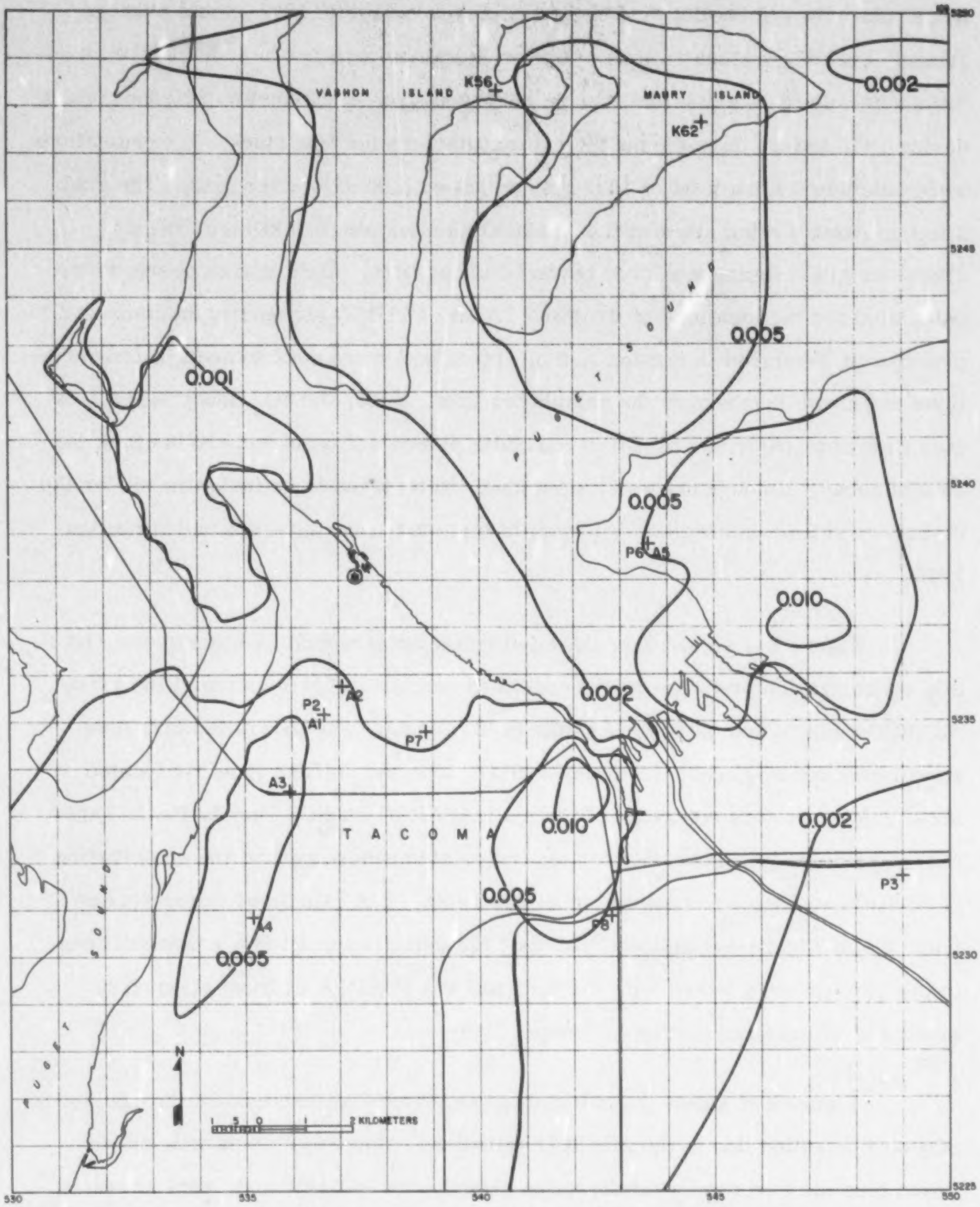

FIGURE 4-1. Calculated isopleths of 1972 annual average ground-level SO_2 concentration in parts per million produced by emissions from all sources. Locations of the ASARCO and PSAPCA SO_2 monitors are indicated by the + symbols.

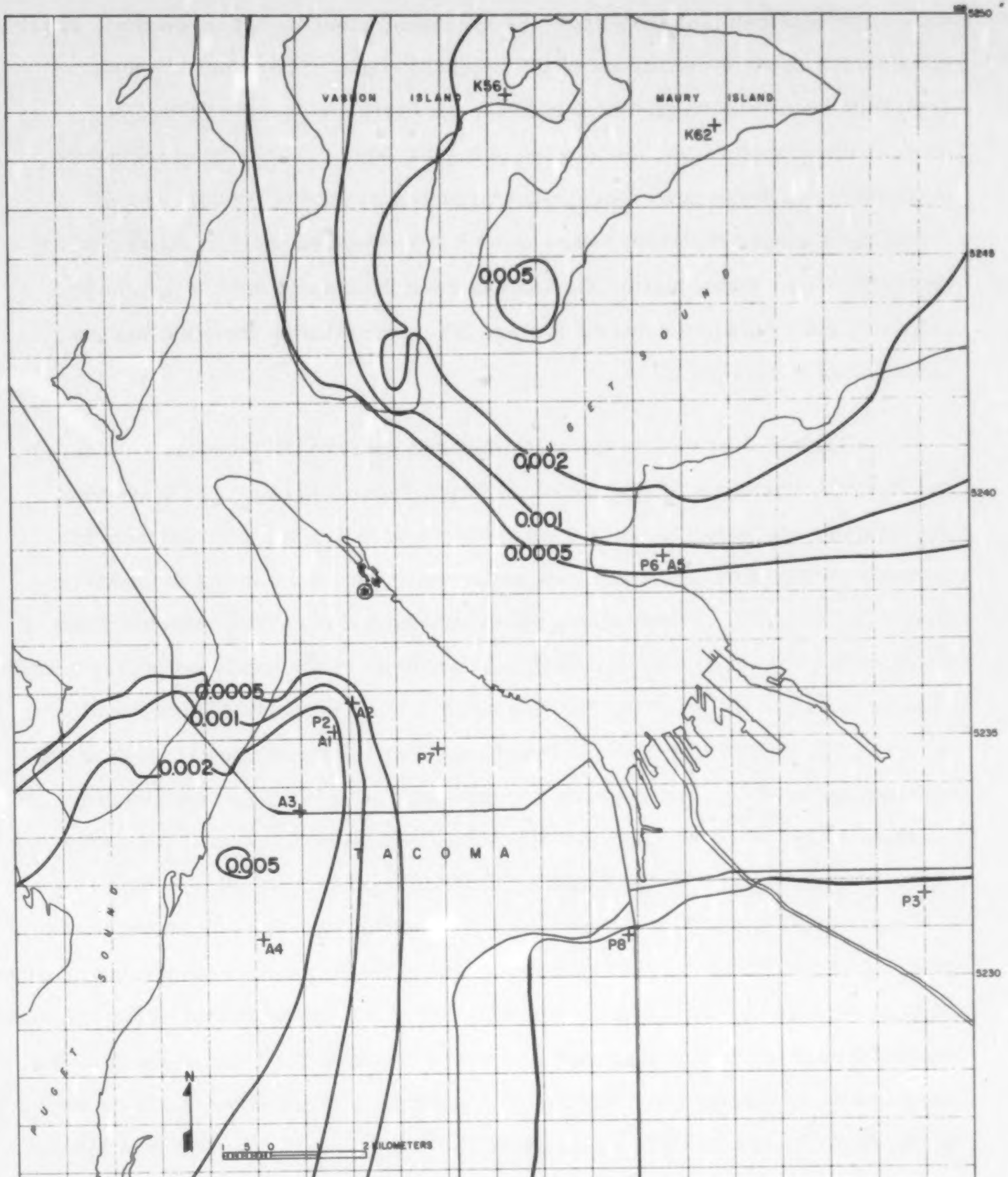

FIGURE 4-2. Calculated isopleths of 1972 annual average ground-level SO_2 concentration in parts per million produced by ASARCO emissions. The star shows the location of the main ASARCO stack.

ASARCO emissions is 0.0083 ppm. This concentration occurs in Tacoma, about 6.3 kilometers south-southwest of the ASARCO stack. The other SO_2 sources contribute about 0.0003 ppm at this point, leading to an annual average SO_2 concentration produced by all sources of 0.0086 ppm. A calculated secondary maximum annual average concentration produced by ASARCO emissions of 0.0056 ppm occurs on Maury Island about 6.9 kilometers north-northeast of the ASARCO stack. Other major SO_2 sources contribute about 0.0022 ppm at this point to yield a calculated annual average SO_2 concentration from all sources combined of 0.0078 ppm.

Table 4-3 compares the calculated and observed SO_2 concentrations for the PSAPCA and ASARCO SO_2 monitors in the Tacoma area. The locations of the monitors are shown by the + symbols in Figures 4-1 and 4-2; the monitor symbols used in the figures are enclosed by parentheses following the monitor names in Table 4-3. In comparing the calculated and observed concentrations, it is important to note that the threshold and accuracy of the two types of SO_2 monitors used by PSAPCA and ASARCO are both equal to 0.01 ppm. With the exception of the ASARCO monitor at N26th and Pearl, all of the observed annual average concentrations are below the accuracy and threshold of the various SO_2 monitors. If we assume that all of the observed annual concentrations have an error range equal to plus or minus one-half the monitor threshold and accuracy of 0.01 ppm (i.e., 0.005 ppm) and if we further assume that the annual concentration measured by PSAPCA at N26th and Pearl is more representative than the corresponding concentration measured by the ASARCO monitor, Table 4-3 shows that all of the calculated concentrations are within the range of error inherent in the measurements. We have no explanation for the difference in the annual average concentrations measured by the ASARCO and PSAPCA monitors at N26th and Pearl. The PSAPCA Meeker and the ASARCO Meeker-Brown monitors, which are also located in close proximity, measured identical annual average concentrations during 1972.

TABLE 4-3

COMPARISON OF CALCULATED AND OBSERVED 1972 ANNUAL AVERAGE GROUND-LEVEL SO_2 CONCENTRATIONS

Monitor	Calculated Concentration (ppm)			Observed Concentration (ppm)
	ASARCO	Other Sources	All Sources	
Vashon Island (K56)	0.0026	0.0016	0.0042	0.005
N26th and Pearl	0.0023	0.0014	0.0036	
PSAPCA(P2)				0.007
ASARCO(A1)*				0.022
Fife Sr. H. S. (P3)	0.0000	0.0012	0.0012	0.003
Meeker	0.0013	0.0045	0.0057	
PSAPCA (P6)				0.004
ASARCO (A5)*				0.004
Adams St (P7)	0.0000	0.0017	0.0018	0.004
Reservoir (A2)*	0.0010	0.0014	0.0024	0.003
Highlands (A3)*	0.0042	0.0015	0.0057	0.005
University Place (A4)*	0.0033	0.0018	0.0051	0.002

*ASARCO SO_2 monitor

It is emphasized that in our 1972 annual average SO_2 concentration calculations, we used a simple hypothetical approximation to represent the effects of the complicated ASARCO SCS operating regime. Our hypothetical SCS operating regime is consistent with the total SO_2 emissions during 1972, but it is only one of a number of possible approximations. We therefore did not expect that our calculated annual concentrations would exactly match the observed concentrations. However, if the uncertainties in the observed concentrations caused by instrument threshold and response are considered, the calculated concentrations are in very good agreement with the air quality data.

4.3 SELECTED SHORT-TERM CALCULATIONS

4.3.1 Calculation Procedures

During the Model Development Phase of our study, we analyzed meteorological and air quality data provided by PSAPCA and selected 20 dates when high SO_2 concentrations were measured for one or more hours at one or more monitors in the Tacoma area. These 20 Short-Term Historical Cases include examples of the three critical meteorological regimes: the critical wind-speed condition, the limited-mixing condition and fumigation. A discussion of these regimes is given in Section 3.2.

The short-term diffusion model described in Section A.3 of Appendix A, including the terrain-adjustment procedures discussed in Section A.5, was used in the calculations for the critical wind-speed and limited-mixing conditions. In applying this model, we varied the wind direction by as much as 10 to 20 degrees to obtain the best correspondence at all SO_2 monitors between calculated and observed concentrations. This procedure was necessary because the hourly mean wind direction at plume stabilization height used in the model calculations must be accurate within 1 or 2 degrees if the plume is to be accurately positioned with respect to fixed points. The mean hourly wind directions obtained from the 15-meter level at the PSAPCA N26th and Pearl station can easily differ from the mean wind direction at the stabilization height of the ASARCO plume by 10 to 20 degrees or more. In the Tacoma cases where high concentrations were concurrently observed at two or more monitors, it was often possible to estimate the wind direction at plume stabilization height within about 1 degree on the basis of a comparison of the calculated and observed concentrations. A more detailed discussion of the sensitivity of short-term ground-level concentrations calculated at fixed points to small errors in the wind direction is given in Appendix E in the discussion of Case 4 (5 July 1972).

The long-term diffusion model described in Section A.4 of Appendix A, including the terrain-adjustment procedures discussed in Section A.5, was used in the fumigation calculations by applying the following procedures:

- The mean wind speed, wind-profile exponent, ambient air temperature and vertical potential temperature gradient used in each fumigation calculation were set equal to values representative of the stable conditions prior to the onset of fumigation
- The wind-direction distribution was assumed to be circular (i.e., $f_{i,j,k,\ell}$ was equal to $\Delta\theta'/2\pi$)
- The vertical turbulent intensity σ_E' was set equal to the value in the unstable surface mixing layer during the fumigation
- The mixing depth was placed at the top of the stabilized ASARCO plume (the plume stabilization height plus 2.15 standard deviations of the vertical concentration distribution at the point of stabilization)

The meteorological inputs used in the calculations for the first 19 Short-Term Historical Cases are listed in Table 4-4. The meteorological inputs for Case 20 (25 December 1974) are included with the discussion of that case (see Appendix E). The wind speeds and the wind directions enclosed by parentheses in Table 4-4 are the hourly values measured at the PSAPCA N26th and Pearl station; the wind directions without parentheses are the wind directions used in the calculations. In each case, the mixing depth and potential temperature gradient were estimated from the most recent Portage Bay EMSU sounding. The McChord Air Force Base cloud-cover observations were combined with the N26th and Pearl wind speeds in assigning a Pasquill Stability category to each hour following the Turner (1964) criteria (see Tables 3-2 and 3-3). The lateral and vertical turbulent intensities corresponding to the various stability categories are given in Table 3-7. The ambient air temperatures in Table 4-4 are the temperatures measured at McChord Air Force Base. The wind-profile exponents were assigned on the basis of the wind speed and Pasquill stability category (see Table 3-8).

Table 4-5 lists the hourly values of the SO_2 emission rates, the volumetric emission rates and the stack exit temperatures for the main ASARCO stack used in the calculations for the first 19 Short-Term Historical Cases. The source inputs for Case 20 are provided with the discussion of that case in Appendix E. For each case listed in Table 4-5, the volumetric emission rate and stack exit temperature were determined on the basis of the number of stack heaters stated in the ASARCO curtailment report to be in operation (see Section 2.1). Where possible, the SO_2 emission rates were estimated from in-stack SO_2 concentration measurements. In the absence of in-stack SO_2 data (see Table 4-5), the emission rates were approximated by the simple equation

$$Q = Q_o \left[\frac{(100 - C)}{100} \right] \tag{4-1}$$

TABLE 4-4

METEOROLOGICAL INPUT PARAMETERS FOR THE FIRST 19 SHORT-TERM HISTORICAL CASES

Case No.	Date	Hour (PST)	Meteorological Regime	Wind* Direction (deg)	Wind Speed (m/sec)	Ambient Air Temp. (°K)	Potential Temperature Gradient (°K/m)	Mixing Depth (m)	Wind Profile Exponent	Pasquill Stability Category
1	29 March 1972	1200	Fumigation	Vrbl	0.940	273	0.008	528	0.30	B
		1300		-----	-----	----	-----	---	-----	---
		1400		-----	-----	----	-----	---	-----	---
2	4 May 1972	2000	Critical Wind Speed	014(009)	5.092	288	0.007	1000	0.15	D
3	4 June 1972	1400	Limited Mixing	014(020)	2.058	295	0.008	600	0.10	C
4	5 July 1972	0300	Limited Mixing	010(007)	1.595	287	0.016	620	0.25	E
5	30 October 1972	0000	Fumigation (Wind Shear)	Vrbl	0.823	283	0.004	600	0.30	B**
		0100		-----	-----	----	-----	---	-----	---
		0200		-----	-----	----	-----	---	-----	---
6	11 October 1972	0300	Critical Wind Speed	018(032)	6.996	276	0.006	530	0.10	D
		0400		012(032)	6.431	276	0.005	530	0.10	D
7	24 October 1972	0900	Limited Mixing	012(042)	1.235	278	0.003	500	0.25	D
8	26 May 1973	1000	Limited Mixing	196(250)	3.087	284	0.003	1500	0.20	D
		2200		013(019)	1.801	281	0.003	1000	0.25	E
		2300		007(026)	2.315	280	0.010	500	0.25	E
9	4 June 1973	0700	Limited Mixing	012(Vrbl)	1.183	283	0.003	1300	0.25	D
		1100		013(329)	1.338	290	0.003	1300	0.10	A
10	19 June 1973	2100	Limited Mixing	013(022)	3.192	292	0.006	1800	0.20	E
11	25 June 1973	1100	Limited Mixing	013(013)	2.264	297	0.003	1000	0.10	B
		1200		018(038)	2.881	298	0.003	1000	0.10	B
		1300		021(047)	2.727	299	0.003	1000	0.10	B

* Wind directions enclosed by parentheses are directions measured at N26th and Pearl; directions not enclosed by parentheses are directions used in calculations.

** Although this stability category did not exist, we estimate that the vertical turbulent intensity in the surface mixing layer was equivalent to the value associated with this category.

TABLE 4-4 (cont'd)

METEOROLOGICAL INPUT PARAMETERS FOR THE FIRST 19 SHORT-TERM HISTORICAL CASES

Case No.	Date	Hour (PST)	Meteorological Regime	Wind* Direction (deg)	Wind Speed (m/sec)	Ambient Air Temp. (°K)	Potential Temperature Gradient (°K/m)	Mixing Depth (m)	Wind Profile Exponent	Pasquill Stability Category
12	30 July 1973	0900	Limited Mixing	224(232)	1.698	288	0.007	450	0.20	D
		1000		223(241)	1.698	290	0.007	450	0.20	D
13	31 July 1973	0500	Limited Mixing	259(255)	2.006	285	0.008	800	0.20	D
		0600		260(251)	2.068	285	0.008	800	0.20	D
		0700		266(266)	1.749	285	0.008	800	0.20	D
		0900		223(245)	1.235	287	0.008	800	0.25	D
		1000		228(228)	1.389	287	0.008	800	0.25	D
14	17 October 1973	1300	Limited Mixing	228(242)	2.624	292	0.004	1150	0.15	C
15	28 January 1974	0300	Critical Wind Speed	218(210)	6.739	281	0.002	600	0.10	D
		0400		218(215)	5.247	281	0.002	600	0.10	D
		1200		218(215)	7.151	282	0.002	600	0.10	D
16	9 February 1974	1000	Fumigation	Vrbl	0.514	276	0.003	736	0.25	B
		1100		-----	-----	----	-----	---	----	---
		1200		-----	-----	----	-----	---	----	---
17	26 February 1974	0400	Limited Mixing	218(196)	2.727	278	0.003	1000	0.20	D
18	6 September 1974	1600	Limited Mixing	018(040)	1.183	297	0.005	1950	0.10	B
19	7 October 1974	0200	Limited Mixing	010(020)	2.161	278	0.017	980	0.25	E
		1200		019(020)	3.447	290	0.003	980	0.10	B
		1300		018(014)	3.653	292	0.003	980	0.10	C

* Wind directions enclosed by parentheses are directions measured at N26th and Pearl; directions not enclosed by parentheses are directions used in calculations.

TABLE 4-5

EMISSIONS DATA FOR THE MAIN ASARCO STACK FOR THE FIRST 19 SHORT-TERM HISTORICAL CASES

Case No.	Date	Hour (PST)	SO_2 Emission Rate (lb/hr)	Volumetric Emission Rate (m^3/sec)	Stack Exit Temperature (°K)
1	29 March 1972	1200	52,000*	300.23	411.0
		1300	------	------	-----
		1400	------	------	-----
2	4 May 1972	2000	31,720*	300.23	411.0
3	4 June 1972	1400	4,420*	300.23	411.0
4	5 July 1972	0300	21,493*	300.23	411.0
5	3 October 1972	0000	52,000*	277.22	388.8
		0100	------	------	-----
		0200	------	------	-----
6	11 October 1972	0300	44,850*	247.63	355.4
		0400	11,960*	300.23	411.0
7	24 October 1972	0900	9,880*	300.23	411.0
8	26 May 1973	1000	40,032	300.23	411.0
		2200	34,778	300.23	411.0
		2300	15,888	300.23	411.0
9	4 June 1973	0700	25,145	300.23	411.0
		1100	4,379	300.23	411.0
10	19 June 1973	2100	17,139	300.23	411.0
11	25 July 1973	1100	6,505	300.23	411.0
		1200	5,880	300.23	411.0
		1300	6,255	300.23	411.0

*Emission rate estimated from Equation (4-1) and the curtailment report

TABLE 4-5 (cont'd)

EMISSIONS DATA FOR THE MAIN ASARCO STACK FOR THE FIRST 19 SHORT-TERM HISTORICAL CASES

Case No.	Date	Hour (PST)	SO_2 Emission Rate (lb/hr)	Volumetric Emission Rate (m^3/sec)	Stack Exit Temperature (°K)
12	30 July 1973	0900	32,776	300.23	411.0
		1000	29,023	300.23	411.0
13	31 July 1973	0500	31,775	300.23	411.0
		0600	27,772	300.23	411.0
		0700	18,515	300.23	411.0
		0900	27,772	300.23	411.0
		1000	18,515	300.23	411.0
14	17 October 1973	1300	32,276	300.23	411.0
15	28 January 1974	0300	30,976	277.22	388.8
		0400	31,650	300.23	411.0
		1200	21,517	300.23	411.0
16	9 February 1974	1000	24,248	277.22	388.8
		1100	------	------	-----
		1200	------	------	-----
17	26 February 1974	0400	38,115	277.22	388.8
18	6 September 1974	1600	4,527	260.95	399.9
19	7 October 1974	0200	33,507	260.95	380.4
		1200	6,067	260.95	399.9
		1300	8,167	260.95	399.9

where Q is the SO_2 emission rate, Q_0 is the maximum uncurtailed emission rate (see Section 2.1) and C is the percent curtailment indicated by the ASARCO curtailment report. In some cases it was necessary to consider the delay time in the downwind transport of stack emissions so that the emissions parameters in Table 4-5 do not always correspond to the hours listed in the table. These cases are specifically noted in the discussion of the individual cases presented in Appendix E.

The concentration calculations for the Short-Term Historical Cases included the contributions of all sources listed in Appendix C except Kaiser Aluminum. As discussed in Section 4.2, Kaiser Aluminum was excluded from the historical calculations because of uncertainties about the emissions parameters. Also, as explained in Section 4.2, the SO_2 decay constant ψ was set equal to zero in all of the snort-term calculations.

4.3.2 Results of the Short-Term Historical Calculations

The results of the concentration calculations for the 20 Short-Term Historical Cases are summarized below and are discussed in detail in Appendix E. Table 4-6 shows the calculated and observed hourly SO_2 concentrations for the critical wind-speed and limited-mixing cases when the observed hourly concentrations exceeded 0.25 ppm. In each case, ASARCO emissions account for at least 99 percent of the calculated concentration. The numbers enclosed by parentheses in the table refer to concentration measurements by the ASARCO SO_2 monitor at N26th and Pearl. The hours listed in Table 4-6 include only those hours when the ASARCO plume was simultaneously detected by two or more SO_2 monitors so that the wind direction could be accurately estimated. Thus, the Maury Island and Vashon Island cases of high SO_2 concentrations are not included in Table 4-6 but are discussed separately. As shown by the mean ratios of calculated and observed concentrations at the bottom of Table 4-6, the calculated concentrations

TABLE 4-6

COMPARISON OF CALCULATED AND OBSERVED SO_2 CONCENTRATIONS FOR CRITICAL WIND-SPEED AND LIMITED-MIXING CASES WHEN THE OBSERVED HOURLY CONCENTRATION EXCEEDED 0.25 PPM

Case No.	Monitor	Observed Concentration* (ppm)	Calculated Concentration (ppm)	Calc. Conc.** / Observed Conc.
2	N26th and Pearl	(1.23)	0.88	(0.72)
	Reservoir	0.27	0.04	0.15
	Highlands	0.73	0.44	0.60
3	N26th and Pearl	0.40 (0.46)	0.25	0.63 (0.54)
4	N26th and Pearl	0.56 (0.68)	0.61	1.09 (0.90)
	Reservoir	0.62	0.64	1.03
6	N26th and Pearl	0.30 (0.22)	0.30	1.00 (1.36)
	N26th and Pearl	0.26 (0.26)	0.23	0.88 (0.88)
7	N26th and Pearl	0.60 (0.46)	0.26	0.43 (0.57)
8	N26th and Pearl	0.32 (0.21)	0.44	1.38 (2.10)
	Reservoir	0.37	0.39	1.05
9	N26th and Pearl	0.37 (0.67)	0.64	1.73 (0.96)
	N26th and Pearl	0.31 (0.21)	0.11	0.35 (0.52)
10	N26th and Pearl	0.25 (0.25)	0.34	1.36 (1.36)
12	McMicken Heights	0.50	0.52	1.04
13	Meeker	0.28	0.28	1.00
	Meeker-Brown	0.31	0.35	1.13
	Meeker	0.38	0.42	1.11
	Meeker-Brown	0.42	0.50	1.19
	Meeker	0.59	0.56	0.95
	Meeker-Brown	0.49	0.53	1.08

TABLE 4-6 (Continued)

Case No.	Monitor	Observed Concentration* (ppm)	Calculated Concentration (ppm)	Calc. Conc. / Observed Conc.**
14	McMicken Heights	0.30	0.09	0.33
	Tukwila	0.41	0.10	0.24
19	N26th and Pearl	0.42 (0.35)	0.87	2.07 (2.49)
	Reservoir	0.50	1.00	2.00
	N26th and Pearl	0.27 (0.17)	0.10	0.37 (0.59)
			Mean Ratio	0.97 (1.00)

*Numbers enclosed by parentheses are concentrations measured by the ASARCO SO_2 monitor at N26th and Pearl.

**Numbers enclosed by parentheses are the ratios of calculated and observed concentrations for the ASARCO monitor at N26th and Pearl.

are, on the average, equal to the observed concentrations. However, some of the calculated and observed concentrations for the individual cases differ by a factor of two or more. Differences of this order between observed and calculated concentrations for a specific hour at individual monitoring sites are not unexpected because of uncertainties in meteorological and emissions input data. Even with the advantage gained in specifying the wind direction by having two or more monitors in the plume, it is still not possible to position the plume with sufficient accuracy to preclude uncertainties of 25 or 30 percent. However, we believe that uncertainties in the ASARCO hourly SO_2 emission rates are the principal cause of the large differences between the calculated and observed concentrations for the individual cases.

Although the Maury Island and Vashon Island cases are not included in Table 4-6, the calculated concentrations at these sites are entirely consistent with the observed concentrations. That is, in each case the concentration calculated by assuming that the ASARCO plume passed directly over the SO_2 monitor is greater than or equal to the observed concentration. For example, the observed concentration on Maury Island for the hour ending at 0400 PST on 26 February 1974 (Case 17) was 0.33 ppm. The corresponding calculated centerline concentration is 0.47 ppm, and a 2- to 3-degree shift in the wind direction used in the model calculations brings the calculated and observed concentrations into exact agreement. We point out that, when the wind blows from the ASARCO stack toward either the Maury Island or the Vashon Island SO_2 monitor, ASARCO is the only source that contributes to the concentration calculated for the monitor.

Table 4-7 shows the calculated and observed SO_2 concentrations for the fumigation cases when the observed hourly concentrations exceeded 0.25 ppm. The calculated concentrations are compared with both the maximum hourly concentration during the period of fumigation and the average concentration during the period of fumigation. As shown by the mean ratios of calculated and observed concentrations

TABLE 4-7

COMPARISON OF CALCULATED AND OBSERVED SO_2 CONCENTRATIONS FOR FUMIGATION CASES WHEN THE OBSERVED HOURLY CONCENTRATION EXCEEDED 0.25 PPM

Case No.	Monitor	Observed Concentration* (ppm)		Calc. Conc. (ppm)	Calculated Conc. ** / Observed Conc.	
		Maximum 1-Hour	Avg. For Period Of Fumigation		Maximum 1-Hour	Avg. For Period Of Fumigation
1	N26th and Pearl	0.19 (0.36)	0.13 (0.21)	0.16	0.84 (0.44)	1.23 (0.76)
	Adams St.	0.36	0.17	0.14	0.39	0.82
	Reservoir	0.38	0.17	0.18	0.47	1.06
2	N26th and Pearl	0.35 (0.16)	0.19 (0.10)	0.14	0.40 (0.88)	0.74 (1.40)
16	N26th and Pearl	0.49 (0.52)	0.40 (0.40)	0.08	0.16 (0.15)	0.20 (0.20)
				Mean Ratios	0.45 (0.47)	0.81 (0.85)

*Numbers enclosed by parentheses are the concentrations measured by the ASARCO monitor at N26th and Pearl.

**Numbers enclosed by parentheses are the ratios of calculated and observed concentrations for the ASARCO monitor at N26th and Pearl.

at the bottom of the table, the calculated fumigation concentrations are, on the average, about half of the maximum hourly concentrations and about 15 to 20 percent lower than the average concentrations. This result is not surprising in view of the assumption of a circular wind distribution in the stable layer prior to fumigation which is necessitated by the lack of wind data at plume height as well as plume observations. Although fumigation is more difficult to model than the critical wind-speed or limited-mixing conditions, our study indicates that the highest ground-level SO_2 concentrations in the Tacoma area are not associated with fumigation. As noted previously, this conclusion is supported by the existing air quality data.

SECTION 5

EVALUATION OF THE CONTROL ALTERNATIVES

5.1 MAXIMUM ANNUAL AVERAGE CONCENTRATIONS

The general meteorological inputs discussed in Section 3.3, the 1972 annual wind distributions for N26th and Pearl given in Appendix B, the ASARCO emissions data for the 21 Control Alternatives given in Section 2.2 and the emissions data for the other major SO_2 sources in the Seattle-Tacoma area listed in Appendix C were used with the long-term concentration model described in Section A.4 of Appendix A to calculate annual average ground-level SO_2 concentrations for each Control Alternative (See Section 2.2). Concentrations were calculated for a total of 1012 grid points on a 20-kilometer by 25-kilometer grid. The grid spacing within 6 kilometers of the ASARCO smelter was 0.5 kilometers; a 1-kilometer grid spacing was used beyond 6 kilometers. Concentrations were also calculated for the locations of the PSAPCA and ASARCO air quality monitors. The procedures described in Section A.5 of Appendix A were used to account for variations in terrain height over the calculation grid.

Table 5-1 lists, for each Control Alternative, the magnitude and location of the calculated maximum annual average ground-level SO_2 concentration produced by ASARCO emissions. Also, the table gives both the calculated contribution, at the point of the maximum ASARCO concentration, of the other major SO_2 sources in the Seattle-Tacoma area and the total concentration calculated for the combined sources. As indicated by the table, Control Alternatives 2, 3, 12 and 14 fail to meet both the National annual air quality standard for SO_2 of 0.03 ppm and the PSAPCA annual standard of 0.02 ppm. Control Alternatives 6 and 16 will meet the National annual standard, but not the PSAPCA annual standard. The calculated maximum annual concentrations for the remaining Control

TABLE 5-1

MAGNITUDES AND LOCATIONS OF CALCULATED MAXIMUM ANNUAL AVERAGE GROUND-LEVEL SO_2 CONCENTRATIONS PRODUCED BY ASARCO EMISSIONS

Control Alternative	Location of Maximum Concentration		Calculated Concentrations (ppm)		
	UTM X (m)	UTM Y (m)	ASARCO	Other Sources	Combined Sources
1	534,500	5,232,500	0.01573	0.00039	0.01612
2	537,000	5,237,500	0.14983	0.00165	0.15148
3	536,000	5,235,000	0.03080	0.00163	0.03243
4	534,500	5,232,500	0.00954	0.00039	0.00993
5	534,500	5,232,500	0.00961	0.00039	0.01000
6	536,000	5,235,000	0.02077	0.00163	0.02240
7	536,000	5,235,000	0.00113	0.00163	0.00276
8	536,000	5,235,000	0.00289	0.00163	0.00452
9	536,000	5,235,000	0.00126	0.00163	0.00289
10	536,000	5,235,000	0.00327	0.00163	0.00490
11	536,000	5,235,000	0.01253	0.00163	0.01416
12	536,000	5,235,000	0.03374	0.00163	0.03537
13	536,000	5,235,000	0.001158	0.00163	0.01321
14	536,000	5,235,000	0.03118	0.00163	0.03281
15	536,000	5,235,000	0.01002	0.00163	0.01165
16	536,000	5,235,000	0.02698	0.00163	0.02861
17	536,000	5,235,000	0.00720	0.00163	0.00883
18	536,000	5,235,000	0.00647	0.00163	0.00810
19	536,000	5,235,000	0.00631	0.00163	0.00794
20	536,000	5,235,000	0.00139	0.00163	0.00302
21	536,000	5,235,000	0.00132	0.00163	0.00295

Alternatives are below both annual standards, even if the SO_2 background produced by the other sources is included.

Figure 5-1 shows the calculated isopleths of annual average ground-level SO_2 concentration produced by ASARCO emissions for Control Alternative 1 (the existing plant configuration without SCS). The isopleth pattern closely resembles the reversed wind-direction distribution shown in Figure 3-1 for N26th and Pearl. The highest calculated concentrations are located south-southwest and northeast of the smelter. According to the calculations, ASARCO emissions have little impact on the long-term ambient air quality in areas northwest and southeast of the smelter. The annual isopleth patterns for the other Control Alternatives also closely resemble the reversed wind-direction distribution for N26th and Pearl.

Figure 5-2 shows, for the combined sources and ASARCO Control Alternative 1, the calculated isopleths of annual average ground-level SO_2 concentration. As can be seen in the figure, calculated SO_2 concentrations above the National and PSAPCA annual air quality standards occur about 11 kilometers southeast of the ASARCO stack in an area essentially unaffected by ASARCO emissions. These high calculated concentrations are almost entirely due to low-level SO_2 emissions from the Kaiser Aluminum Plant. Assuming that the stack and emissions parameters used in the calculations are correct, Kaiser Aluminum has a greater impact on long-term ambient air quality than the ASARCO smelter.

5.2 MAXIMUM MONTHLY AVERAGE CONCENTRATIONS

In addition to the PSAPCA annual ambient air quality standard of 0.02 ppm, there is a PSAPCA monthly standard of 0.04 ppm. During 1972, the maximum monthly average ground-level SO_2 concentration measured by the PSAPCA monitor at N26th and Pearl was 0.016 ppm for the month of October. This is 2.29 times

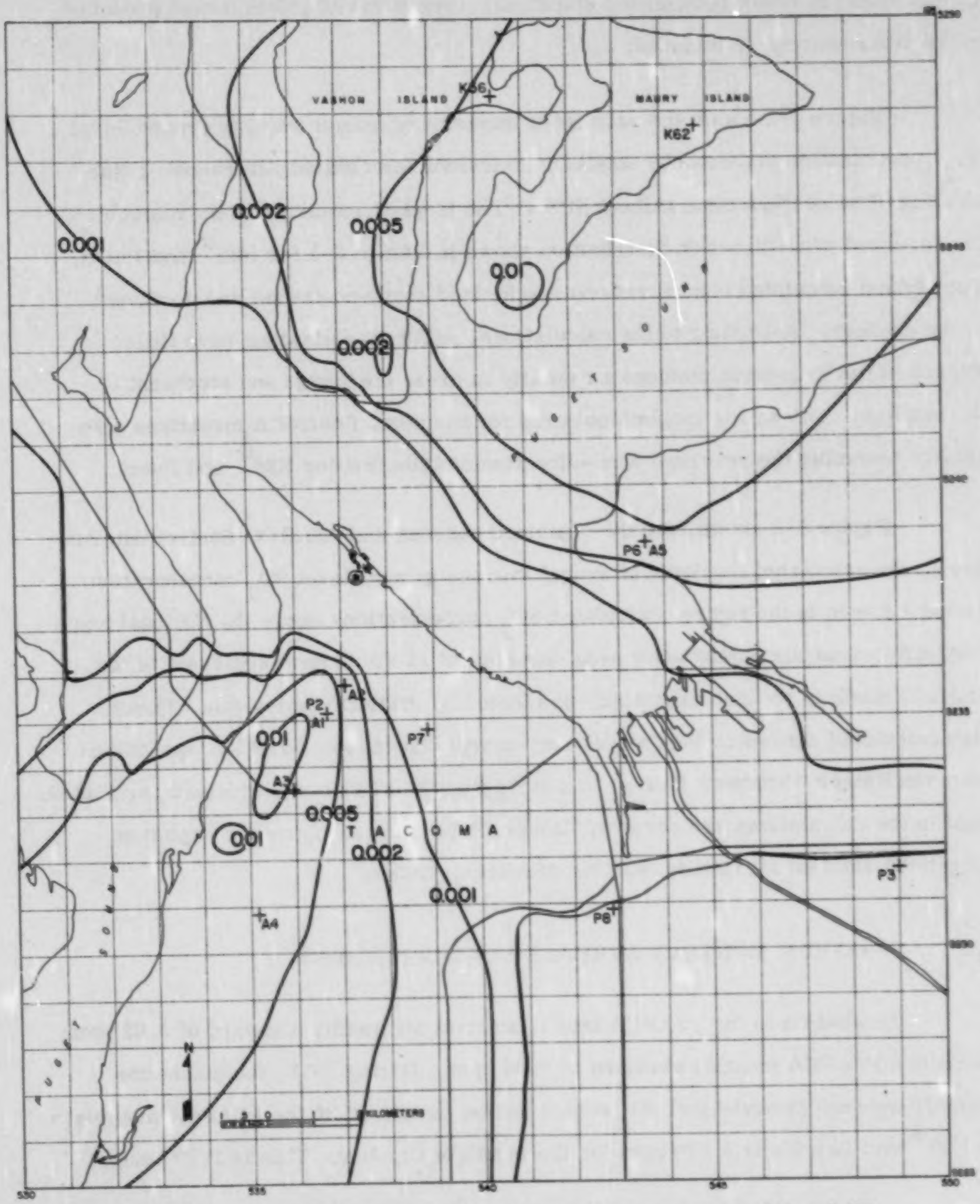

FIGURE 5-1. Calculated isopleths of annual average ground-level SO_2 concentration in parts per million produced by ASARCO emissions for Control Alternative 1.

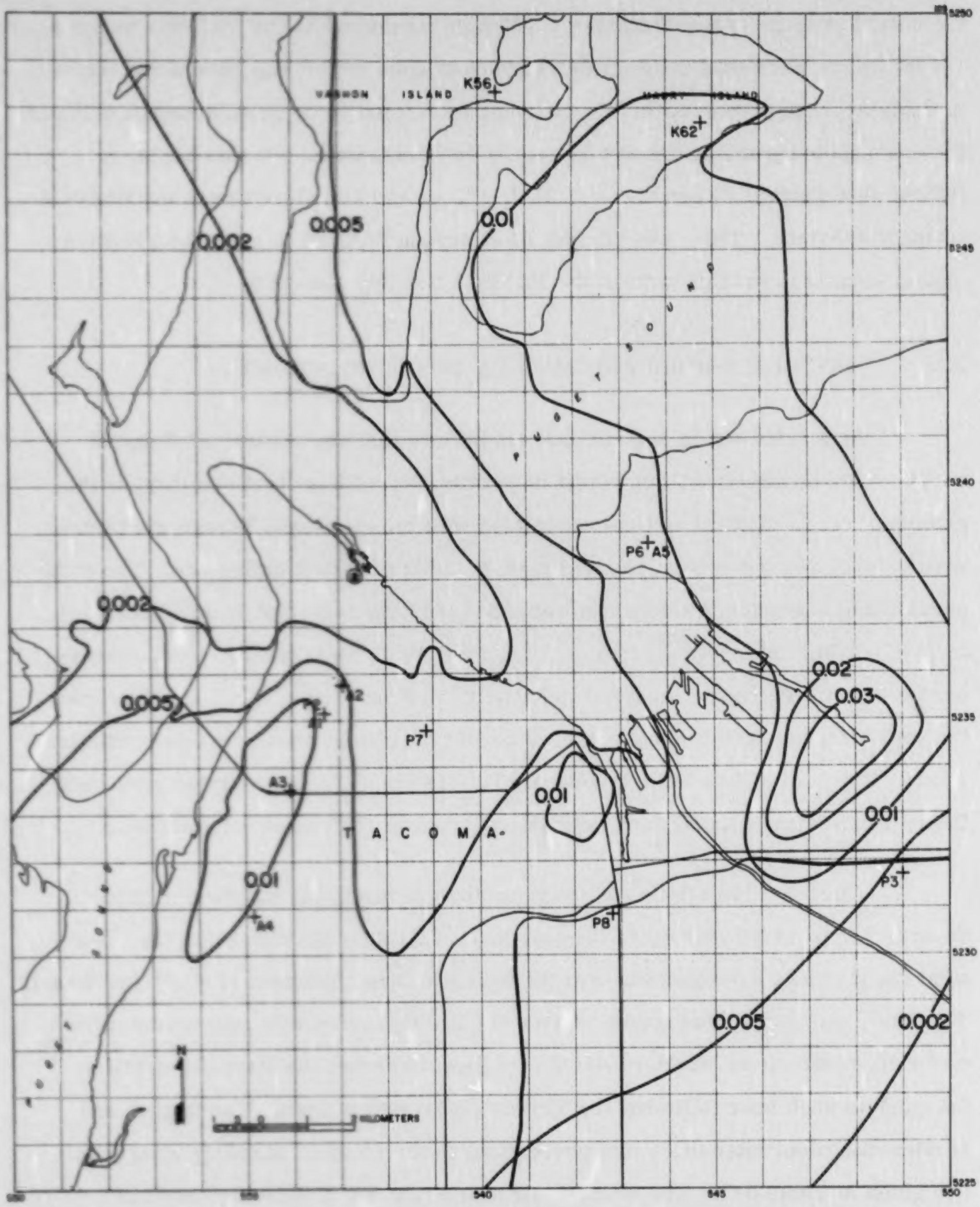

FIGURE 5-2. Calculated isopleths of annual average ground-level SO_2 concentration in parts per million produced by the combined sources for Control Alternative 1.

the annual average concentration of 0.007 ppm measured by the PSAPCA monitor. We interpret this result to mean that the worst-case month will have a maximum monthly average ground-level SO_2 concentration equal to or greater than 2.3 times the corresponding maximum annual average concentration. On this basis, it follows that Control Alternatives 2, 3, 6, 12, 14 and 16 will not meet the PSAPCA monthly standard. Thus, the Control Alternatives that fail to meet the PSAPCA annual standard also fail to meet the PSAPCA monthly standard.

5.3 MAXIMUM 3-HOUR AND 24-HOUR CONCENTRATIONS

As pointed out in Section 3.2, we believe that the critical wind-speed condition (moderate-to-strong winds in combination with neutral stability) is the principal meteorological regime associated with the maximum 3-hour and 24-hour ground-level SO_2 concentrations produced by ASARCO stack emissions. The wind-persistence statistics presented in Table 3-5 indicate that wind speeds above 5.1 meters per second at N26th and Pearl are most likely to persist from the north-northeast. We therefore analyzed the hourly wind data from N26th and Pearl for the year 1972 in order to isolate a 24-hour period with persistent north-northeast winds. The hourly data for this selected "worst-case" 24-hour period were used in the short-term concentration calculations for the 21 Control Alternatives.

Table 5-2 lists the hourly meteorological inputs for the "worst-case" 24-hour period (1400 PST on 24 January to 1300 PST on 25 January 1972). The wind speeds and wind directions are the hourly values measured at N26th and Pearl. The N26th and Pearl wind speeds were used in conjunction with concurrent cloud-cover observations at McChord Air Force Base to assign the Pasquill stability category to each hour following the Turner (1964) procedures. The lateral and vertical turbulent intensities that correspond to the Pasquill stability categories are given in Table 3-7. The ambient air temperatures in Table 5-2 are the

TABLE 5-2

METEOROLOGICAL INPUTS FOR THE WORST-CASE 24-HOUR PERIOD

Hour	Wind Direction (deg)	Wind Speed (m/sec)	Ambient Air Temperature (°K)	Potential Temperature Gradient (°K/m)	Mixing Depth (m)	Wind Profile Exponent p	Pasquill Stability Category
00	020	4.116	274	0.003	690	0.15	D
01	020	5.144	274	0.003	690	0.15	D
02	020	5.144	274	0.003	690	0.15	D
03	020	6.173	274	0.003	875	0.10	D
04	020	5.659	274	0.003	875	0.10	D
05	020	6.173	273	0.003	875	0.10	D
06	020	7.717	273	0.003	875	0.10	D
07	020	8.231	273	0.003	875	0.10	D
08	020	8.231	272	0.003	875	0.10	D
09	020	10.803	271	0.003	1000	0.10	D
10	020	10.803	270	0.003	1000	0.10	D
11	020	11.318	270	0.003	1000	0.10	D
12	020	10.803	270	0.003	1000	0.10	D
13	020	10.803	270	0.003	1000	0.10	D
14	020	9.774	270	0.003	1000	0.10	D
15	020	10.289	270	0.003	1000	0.10	D
16	030	10.803	269	0.003	1000	0.10	D
17	020	9.774	269	0.003	1000	0.10	D
18	030	8.745	269	0.003	1000	0.10	D
19	020	7.202	269	0.003	875	0.10	D
20	020	7.202	269	0.003	875	0.10	D
21	030	7.717	269	0.003	875	0.10	D
22	030	7.202	269	0.003	875	0.10	D
23	040	6.688	269	0.003	875	0.10	D

temperatures measured at McChord Air Force Base. For each hour, the wind-speed and stability categories were used to select the wind-profile exponent from Table 3-8. Because no Portage Bay EMSU soundings were made during this period, we set the potential temperature gradient equal to the moist-adiabatic value which appears to be characteristically associated with the occurrence of high short-term SO_2 concentrations (see Section 4.3). The hourly mixing depths were assigned on the basis of wind speed and stability (see Table 3-9).

The meteorological inputs in Table 5-2, the ASARCO emissions data for the 21 Control Alternatives (see Section 2.2) and the emissions data for the other major SO_2 sources in the Seattle-Tacoma area listed in Appendix C were used with the short-term concentration model described in Section A.3 of Appendix A to calculate 1-, 3- and 24-hour average ground-level SO_2 concentrations for each Control Alternative. Concentrations were calculated for a total of 1012 grid points on a 20-kilometer by 25-kilometer grid. The grid spacing within 6 kilometers of the ASARCO smelter was 0.5 kilometers; a 1-kilometer grid spacing was used beyond 6 kilometers. Concentrations were also calculated for the locations of the PSAPCA and ASARCO SO_2 monitors. The procedures described in Section A.5 of Appendix A were used to account for variations in terrain height over the calculation grid.

Table 5-3 lists the locations and the magnitudes of the calculated maximum 3-hour ground-level SO_2 concentrations produced by ASARCO emissions for the various Control Alternatives. All of the calculated maximum 3-hour concentrations occur during the first 3 hours of the "worst-case" 24-hour period (see Table 5-2). Because the average rather than the maximum uncurtailed SO_2 emission rate was used in the calculations for Control Alternative 1 (the existing configuration without SCS) and because ASARCO has had difficulty in maintaining 51-percent permanent control (see Section 2.2), the calculated maximum 3-hour concentration given in Table 5-3 for this case may be too low.

TABLE 5-3

MAGNITUDES AND LOCATIONS OF CALCULATED MAXIMUM 3-HOUR GROUND-LEVEL SO_2 CONCENTRATIONS PRODUCED BY BY ASARCO EMISSIONS

Control Alternative No.	Location of Maximum Concentration		Calculated Concentrations (ppm)		
	UTM X (m)	UTM Y (m)	ASARCO	Other Sources	Combined Sources
1	536,000	5,234,500	0.63307	0.00214	0.63521
2	537,000	5,237,000	0.89401	0.00229	0.89630
3	536,000	5,234,500	0.88399	0.00214	0.88613
4	536,000	5,234,500	0.41222	0.00214	0.41436
5	536,000	5,234,500	0.43077	0.00214	0.43291
6	536,000	5,234,500	0.59254	0.00214	0.59468
7	536,000	5,234,500	0.05995	0.00214	0.06209
8	536,000	5,234,500	0.08214	0.00214	0.08428
9	536,000	5,234,500	0.06788	0.00214	0.07002
10	536,000	5,234,500	0.09336	0.00214	0.09550
11	536,000	5,234,500	0.70281	0.00214	0.70495
12	536,000	5,234,500	0.97214	0.00214	0.97428
13	536,000	5,234,500	0.64945	0.00214	0.65159
14	536,000	5,234,500	0.89822	0.00214	0.90036
15	536,000	5,234,500	0.56201	0.00214	0.56415
16	536,000	5,234,500	0.77724	0.00214	0.77938
17	536,000	5,234,500	0.40348	0.00214	0.40562
18	536,000	5,234,500	0.36248	0.00214	0.36462
19	536,000	5,234,500	0.35341	0.00214	0.35555
20	536,000	5,234,500	0.07486	0.00214	0.07700
21	536,000	5,234,500	0.07032	0.00214	0.07246

As shown by Table 5-3, Control Alternatives 1, 2, 3, 6, 11, 12, 13, 14, 15 and 16 have calculated maximum 3-hour ground-level SO_2 concentrations that exceed the National 3-hour ambient air quality standard of 0.50 ppm. For these Control Alternatives, the calculated second highest 3-hour concentrations during the worst case 24-hour period also exceed the 3-hour standard. It should be noted that, under the selected "worst-case" meteorological conditions, the other major SO_2 sources in the Seattle-Tacoma area do not significantly contribute to the calculated concentrations at the locations of the maximum concentrations produced by ASARCO emissions.

Table 5-4 lists, for each Control Alternative, the location and magnitude of the calculated maximum 24-hour average ground-level SO_2 concentration produced by ASARCO emissions. As noted above, the calculated 24-hour concentration for Control Alternative 1 may be too low. The results of the calculations indicate that Control Alternatives 1, 2, 3, 4, 5, 6, 11, 12, 13, 14, 15, 16, 17, 18 and 19 will not meet the National 24-hour ambient air quality standard of 0.14 ppm or the PSAPCA 24-hour ambient air quality standard of 0.10 ppm.

The meteorological inputs for the "worst-case" 24-hour period include a 20-hour persistence of north-northeast winds above 5.1 meters per second. According to Table 3-5, this condition can be expected to occur about once per year. Table 3-5 also indicates that north-northeast winds above 5.1 meters per second can be expected to persist for 14 or more hours about twice per year. It follows that the second highest 24-hour average SO_2 concentrations will be approximately 70 percent (14/20) of the "worst-case" 24-hour concentrations listed in Table 5-4. Thus, the second highest 24-hour average SO_2 concentrations for Control Alternatives 1, 2, 3, 4, 5, 6, 11, 12, 13, 14, 15, 16, 17, 18 and 19 should also exceed both the National and the PSAPCA 24-hour standards.

TABLE 5-4

MAGNITUDES AND LOCATIONS OF CALCULATED MAXIMUM 24-HOUR GROUND-LEVEL SO_2 CONCENTRATIONS PRODUCED BY ASARCO EMISSIONS

Control Alternative	Location of Maximum Concentration		Calculated Concentrations (ppm)		
	UTM X (m)	UTM Y (m)	ASARCO	Other Sources	Combined Sources
1	536,000	5,234,500	0.42514	0.00088	0.42602
2	536,500	5,235,500	0.55083	0.00091	0.55174
3	536,000	5,234,500	0.59124	0.00088	0.59212
4	536,000	5,234,500	0.26844	0.00088	0.26932
5	536,500	5,235,500	0.28792	0.00091	0.28883
6	536,000	5,234,500	0.37668	0.00088	0.37756
7	536,500	5,235,500	0.04062	0.00091	0.04153
8	536,000	5,234,500	0.05152	0.00088	0.05240
9	536,500	5,235,500	0.04541	0.00091	0.04632
10	536,000	5,234,500	0.05925	0.00088	0.06013
11	536,500	5,235,500	0.46187	0.00091	0.46278
12	536,000	5,234,500	0.62958	0.00088	0.63046
13	536,500	5,235,500	0.42698	0.00091	0.42789
14	536,000	5,234,500	0.58148	0.00088	0.58236
15	536,500	5,235,500	0.36958	0.00091	0.37049
16	536,000	5,234,500	0.50304	0.00088	0.50392
17	536,500	5,235,500	0.26543	0.00091	0.26634
18	536,500	5,235,500	0.23841	0.00091	0.23932
19	536,500	5,235,500	0.23251	0.00091	0.23342
20	536,500	5,235,500	0.05008	0.00091	0.05099
21	535,500	5,234,500	0.04763	0.00091	0.04854

We point out that the area of high calculated short-term ground-level SO_2 concentrations for the selected worst-case 24-hour period is west of the existing SO_2 monitoring network. Thus, the maximum hourly ground-level SO_2 concentrations produced by actual ASARCO emissions during this period probably went undetected. The PSAPCA monitor at N26th and Pearl, which is on the eastern edge of this area, measured moderate hourly SO_2 concentrations (0.05 to 0.28 ppm) during 11 hours of this period.

As noted in Section 5.1, our calculations suggest that low-level SO_2 emissions from Kaiser Aluminum have a greater impact on long-term ambient air quality than the ASARCO stack emissions. However, the maximum 24-hour SO_2 concentration calculated for Kaiser Aluminum during the worst-case 24-hour period is only 0.04 ppm. This follows because the meteorological condition that maximizes the ground-level concentrations produced by buoyant stack emissions (the critical wind-speed condition) minimizes the ground-level concentrations produced by low-level emissions. Light winds in combination with a stable thermal stratification characteristic of air stagnation comprise the meteorological condition that typically produces the highest ground-level concentrations from low-level emissions.

5.4 MAXIMUM HOURLY AND 5-MINUTE CONCENTRATIONS

It follows from the preceding discussions that only Control Alternatives 7, 8, 9, 10, 20 and 21 will meet both the National and PSAPCA SO_2 ambient air quality standards for averaging times greater than one hour. We have assumed that the Control Alternatives that do not meet all PSAPCA and National ambient air quality standards for averaging times greater than one hour also do not meet the 5-minute and hourly PSAPCA standards. Thus, only the six Control Alternatives cited above are considered in this section.

It should be noted that the maximum hourly ground-level SO_2 concentrations calculated for the Control Alternatives using the meteorological inputs in Table 5-2 may not necessarily represent the actual maximum hourly concentrations for the following reasons:

- The density of the 0.5-kilometer grid spacing may not be adequate to isolate locations of the maximum hourly ground-level concentrations
- Meteorological conditions that result in the highest hourly ground-level concentrations may differ from the persistent moderate-to-strong wind conditions associated with maximum 3-hour and 24-hour concentrations

For the six Control Alternatives with the potential to meet all PSAPCA air quality standards (Control Alternative 7, 8, 9, 10, 20 and 21), we used the general meteorological inputs given in Section 3.3 and Equation (A-41) in Appendix A to calculate, for each combination of wind-speed and stability categories, maximum hourly ground-level SO_2 concentrations. In these calculations, we assumed the average terrain elevation within Tacoma to be 100 meters (330 feet) above mean sea level (see Figure 1-1). The annual frequencies of occurrence of the various combinations of wind speed and stability at N26th and Pearl (see Appendix B) were used to estimate the total number of hours per year of hourly SO_2 concentrations above the PSAPCA hourly standards of 0.40 and 0.25 ppm.

Table 5-5 presents, for the six Control Alternatives, the calculated maximum hourly ground-level SO_2 concentrations and Table 5-6 presents the estimated number of hours per year of hourly concentrations above the PSAPCA hourly standards. It should be noted that two pairs of Control Alternatives (7 and 8; 9 and 10) are identical except that the existing 172-meter (565-foot) main stack is used for Control

TABLE 5-5

CALCULATED MAXIMUM HOURLY GROUND-LEVEL SO_2 CONCENTRATIONS

Control Alternative	Maximum Hourly SO_2 Concentration (ppm)
7	0.14239
8	0.31465
9	0.16223
10	0.39443
20	0.17891
21	0.17052

TABLE 5-6

ESTIMATED NUMBER OF HOURS PER YEAR THAT THE MAXIMUM GROUND-LEVEL SO_2 CONCENTRATION EXCEEDS THE PSAPCA HOURLY STANDARDS

Control Alternative	Hours Per Year That The Hourly Concentration Exceeds	
	0.40 ppm*	0.25 ppm**
7	0	0
8	0	948
9	0	0
10	0	948
20	0	0
21	0	0

*PSAPCA ambient air quality standard, never to be exceeded.

**PSAPCA ambient air quality standard, not to be exceeded at any given point more than twice in any 7-day period.

Alternatives 7 and 9 while a new 152-meter (500-foot) main stack is used for Control Alternatives 8 and 10. Also, the base of the new main stack is assumed to be located 9 meters (30 feet) below the base of the existing stack. Because the new main stack is shorter and the base is at a lower elevation than the existing stack, the maximum concentrations calculated for the new main stack are larger than the corresponding concentrations calculated for the existing main stack.

The results of the calculations presented in Tables 5-5 and 5-6 may be summarized as follows:

- Control Alternatives 7, 9, 20 and 21 clearly meet all PSAPCA hourly standards
- The calculated maximum hourly concentrations for Control Alternatives 8 and 10 are relatively low and concentrations above 0.25 ppm are estimated to occur so infrequently that we believe it is likely that these Control Alternatives will be in marginal compliance with the PSAPCA hourly standard of 0.25 ppm (not to be exceeded at any given point more than twice in any 7-day period)

The conclusion given above that Control Alternatives 8 and 10 are likely to be in marginal compliance with the PSAPCA hourly standard of 0.25 ppm requires additional explanation. PSAPCA Regulation I permits two hourly SO_2 concentrations above 0.25 ppm (but less than 0.40 ppm) at any given point during a 7-day period. Assuming that these excursions are evenly spaced in time, a single point can experience up to 104 excursions per year without violating the PSAPCA hourly standard of 0.25 ppm. Table 5-6 lists, for each Control Alternative, the total number of hours per year that the calculated maximum hourly ground-level SO_2 concentration exceeds 0.25 ppm. Trial calculations for Control Alternative 1 using the procedures described in Section A.6 of Appendix A indicate that no single point will experience more than about 4 percent of this total. It follows that, at the point most frequently affected by ASARCO emissions, Control Alternatives 8 and 10 will cause excursions above the 0.25 ppm standard about 40 hours per year. In each case, it is possible that three of these excursions could occur within a 7-day period. Thus, infrequent violations of the 0.25 ppm standard are possible for Control Alternatives 8 and 10.

The only other short-term PSAPCA SO_2 ambient air quality standard that must be considered is the PSAPCA 5-minute standard of 1.0 ppm, not to be exceeded more than once in any 8-hour period. Applying the $t^{-1/5}$ law (Osipov, 1972 and others) to the Control Alternatives listed in Table 5-5, none of the calculated maximum 5-minute concentrations exceeds 1.0 ppm. We conclude that the Control Alternatives that will meet the PSAPCA hourly standards will also meet the PSAPCA 5-minute standard.

SECTION 6

EVALUATION OF THE EFFECTIVENESS OF THE ASARCO SCS

6.1 BACKGROUND: THE SCS CONCEPT

A Supplementary Control System (SCS) is a system that curtails stack pollutant emissions during periods when meteorological conditions conducive to ground-level concentrations in excess of applicable air quality standards exist or are anticipated to exist.

The U. S. Environmental Protection Agency (1976) has recently published an SCS guidelines document describing the basic elements, functions, development and operation of Supplementary Control Systems. As explained in the EPA guidelines document, an SCS operates in two different modes:

- An open-loop mode for normal smelter or plant operations in which a predictive model that quantitatively relates stack SO_2 emissions, stack parameters and meteorological parameters to maximum short-term ground-level SO_2 concentrations is routinely used to determine the emissions curtailment required to prevent violations of the applicable air quality standards
- A closed-loop mode used to curtail emissions in emergency situations when air quality measurements from monitors located in the vicinity of a smelter or power plant show that short-term air quality standards are threatened

There are many technical as well as logistical and economic problems associated with the development and operation of an SCS. These problems stem in part from the uniqueness of the meteorological, topographical and source

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parameters associated with each industrial smelter or fossil fuel power plant. The meteorological parameters include wind circulation patterns and atmospheric stability conditions controlling the transport and dispersion of stack discharges. Topographical parameters include prominent terrain features that channel or block the normal airflow and/or induce vortices that affect the dispersion of stack plumes, as well as terrain elevations that are significantly higher than the elevation of the stack base. Source parameters include, in addition to the usual stack parameters (stack height, exit velocity, exit temperature, effluent composition and density, and pollutant discharge rate), plant layout of buildings and other structures that may produce wake effects, as well as process details that determine the rate of emissions curtailment. Other SCS technical problems include the development of a predictive model that accurately relates stack and fugitive emissions to ambient air quality, the design and operation of automated in-stack measurement systems, air quality monitoring networks, meteorological measurement networks, as well as automated data-acquisition, data-processing, data-storage and data-retrieval systems. Additional problems arise from the fact that the detailed meteorological data, air quality data and emissions/stack parameter data required for designing an SCS are generally not available. Consequently, it is usually necessary to revise and update the original SCS design as the result of the experience gained during a year or more of actual operation.

6.2 DESCRIPTION OF THE ASARCO SCS

As stated in the ASARCO Supplementary Control System Operating Manual (Welch, 1976), the objective of the Tacoma Plant SCS is to maintain an air quality that meets the local, state and National ambient air quality standards by keeping a proper balance between the SO_2 emission rate and the meteorological elements of wind and stability that determine the degree of plume dispersion and thus the sulfur dioxide concentration. Development of the ASARCO SCS started in 1970 well before any detailed guidelines such as those recently published by EPA were available. The rationale for the ASARCO SCS stems principally from the stringent PSAPCA short-term SO_2 standards, particularly the 5-minute and 1-hour standards, which we believe cannot normally be met with either the 17-percent or 51-percent constant emissions controls. The basic operational concept of the ASARCO SCS involves the use of meteorological forecasts to anticipate the times when the main stack plume will be in contact with the ground, as the result of turbulent mixing in the air layer between the plume stabilization height and the earth's surface, and the curtailment of stack emissions and/or the use of stack heaters sufficiently in advance of these times to prevent the occurrence of concentrations that approach or exceed the PSAPCA short-term air quality standards. The required emissions curtailments are quite large. According to the emission rate guidelines in the ASARCO SCS Operating Manual, they range from about 50 to 90 percent or more of the uncurtailed emission rate for 51-percent constant emissions control, depending on meteorological conditions. Because of the time required to effect the requisite emissions curtailments and the time before the reduced stack emissions can affect the air quality at the ASARCO or PSAPCA monitors, there is an inherent time delay in the ASARCO SCS of 20 minutes to 1 hour or more (see Section 6.3). It follows that the occurrence of high 5-minute and 1-hour concentrations at the monitors must be anticipated in advance and appropriate curtailment actions must be taken in advance if violations of the corresponding air quality standards are to be prevented. These facts explain the emphasis placed on meteorological forecasting in the routine operation of the ASARCO SCS and clearly demonstrate that the ASARCO SCS cannot be operated as a closed-loop system (i.e., by basing curtailment actions on air quality observations at the monitors) to achieve compliance with the 5-minute and 1-hour PSAPCA air quality standards. Although there are some exceptions, the ASARCO SCS appears to be generally capable of preventing violations of the of the National 3-hour and 24-hour SO_2 ambient air quality standards by a closed-loop mode of operation, especially because of the curtailment actions taken to attempt to prevent violations of the PSAPCA 5-minute and 1-hour standards.

The ASARCO SCS is staffed by six professional meteorologists. Curtailment decisions are made by the meteorologist on duty at the Emissions Control Center located in the smelter administration building. According to the SCS Operating Manual, the normal daily SCS operating routine is divided into three phases:

(1) Initial Phase, corresponding to the early part of the day when the ASARCO plume is typically above the surface mixing layer and not in contact with the ground. In this phase, a meteorological forecast is made of the:

- Time at which the top of the surface mixing layer is expected to reach plume level
- Intensity of the initial mixing
- Wind speeds at the surface and at plume level during the initial mixing period

(2) Intermediate Phase, corresponding to the middle part of the day when the ASARCO plume is in the surface mixing layer and is in contact with the ground. In this phase, predictions are made of the:

- Degree of mixing
- Wind flow at the surface and at plume height
- Stability within the mixing layer

(3) Final Phase, corresponding to the latter part of the day when the surface mixing layer contracts and the ASARCO plume ceases to mix to the ground. In this phase, curtailment is reduced and the emission rate increased as the meteorological indicators show increasing stability and the plume moves out of the surface mixing layer.

The ASARCO SCS Operating Manual provides, for the first two phases, emission rate guidelines (expressed as fractions of the uncurtailed rate ranging from about 0.10 to 0.50) to assist the meteorologist in making curtailment decisions. According to the SCS Manual, specific emission rates cannot be designated in the Manual because of the almost infinite number of possible meteorological conditions. The actual emission rate can thus only be determined by the experienced judgment of the meteorologist who must base his decision upon his interpretation of the meteorological conditions. During the Final Phase, the emission rate is increased as meteorological indicators show increasing stability and all curtailment action is normally stopped when the tower temperature difference* shows an inversion greater than 3 degrees Fahrenheit and the insolation is less than 0.05 gram calories per square centimeter per minute. The ASARCO SCS Operating Manual also specifies guidelines for dealing with upset conditions, the occurrence of unexpected high concentrations at any ambient monitoring stations that are projected to approach or exceed an air quality standard, air stagnation episodes and the operation of the stack heaters.

The following meteorological, air quality and smelter operation data are received at the Emission Control Center by telemetry or teletype:

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*The tower in question is not identified in the ASARCO SCS Operating Manual; we believe it is the 150-foot microwave tower at N26th and Pearl.

Air Quality Data

- SO_2 concentrations from five ASARCO monitors are telemetered to a multipoint recorder; the monitors are ASARCO Autometers and operate on a 30-minute cycle

- SO_2 concentrations are received by teletype from 14 PSAPCA SO_2 monitors; normally, 5-minute average SO_2 concentrations at each monitor are received every 15 minutes and hourly average and 24-hour running average SO_2 concentrations at each monitor are received each hour

- 30-Minute average coefficients of haze (CoHs) at each PSAPCA monitor site are received by teletype every half hour and hourly average and 24-hour running average CoHs are received each hour

Meteorological Data

- Wind speed and wind direction data are telemetered from all ASARCO SO_2 monitor sites except University Place, from the top of a 150-foot tower at N26th and Pearl, and from a tower located at N48th and Baltimore

- Temperature data are telemetered from sensors located at the top of the 150-foot tower at N26th and Pearl, the nearby ASARCO monitor site, the 510-foot level of the main stack and at the Emissions Control Center; also, temperature profile data from an acoustic sounder located outside the Emissions Control Center are continuously recorded

- Wind speed and wind direction data (5-minute and hourly averages) are received by teletype from all fifteen PSAPCA wind stations

- The Emission Control Center also has a teletype receiver for the National Weather Service Circuit A transmissions, a teletype receiver-transmitter for a local National Weather Service network and a facsimile recorder for the NAFAX circuit

Smelter Operation Data

The following in-plant telemetered information is recorded in the Emissions Control Center

- Converter operations
- Reverberatory furnace feed rate
- Stack heater operations
- Stack gas SO_2 concentrations
- Acid plant and liquid SO_2 plant gas flows

6.3 CRITIQUE OF THE ASARCO SCS

Comparison of the ASARCO SCS with the SCS concept described in the recently-published EPA guidelines document (U. S. Environmental Protection Agency, 1976) shows the principal difference to be in the open-loop mode of operation. The ASARCO SCS does not use a predictive model directly relating the stack SO_2 emission rate, stack parameters (stack height, exit velocity or flow rate and exit temperature) and meteorological parameters to ground-level concentrations. Although some attempts have apparently been made to develop a predictive model for the ASARCO Tacoma smelter, these were not successful. In place of a predictive model of the type specified in the EPA guidelines, ASARCO has substituted the meteorological forecasting procedures described above coupled with the judgment and experience of the meteorologist on duty at the SCS Emissions Control Center to determine the proper emission rate and stack heater operation required to prevent violations of the short-term air quality standards. The current operational procedures of the ASARCO SCS appear to be almost entirely based on the experience gained from operating the system over the past six years without recourse to diffusion modeling of the impact of the smelter SO_2 emissions.

The combination of this strong empirical base with the high degree of subjectivity inherent in the meteorological prediction procedures and curtailment decisions makes an objective analysis of the ASARCO SCS procedures very difficult. For example, we have had considerable difficulty in reconciling SO_2 emission rates for the historical cases used in the selection and testing of short-term diffusion models (see Section 4.3 and Appendix E) indicated by the curtailment reports supplied to PSAPCA by ASARCO with similar rates estimated from the in-stack SO_2 monitor readings. Figure 6-1 shows a graph of average hourly SO_2 emission rates for 25 July 1973 estimated from curtailment reports and from in-stack SO_2 concentration data using Equation (4-1). Reasonably close agreement, which may be fortuitous, occurs only for about 6 of the 24 hours. The largest differences occur during the early morning and nighttime hours when the percent curtailment is small or zero and during the middle of the day when the percent curtailment is 90 percent or larger. We interpret Figure 6-1 to mean that there is no accurate method for determining the actual SO_2 emission rate from the ASARCO curtailment reports and that the emission rate for 100 percent curtailment, prior to the liquid SO_2 plant, was approximately 4,000 pounds of SO_2 per hour.

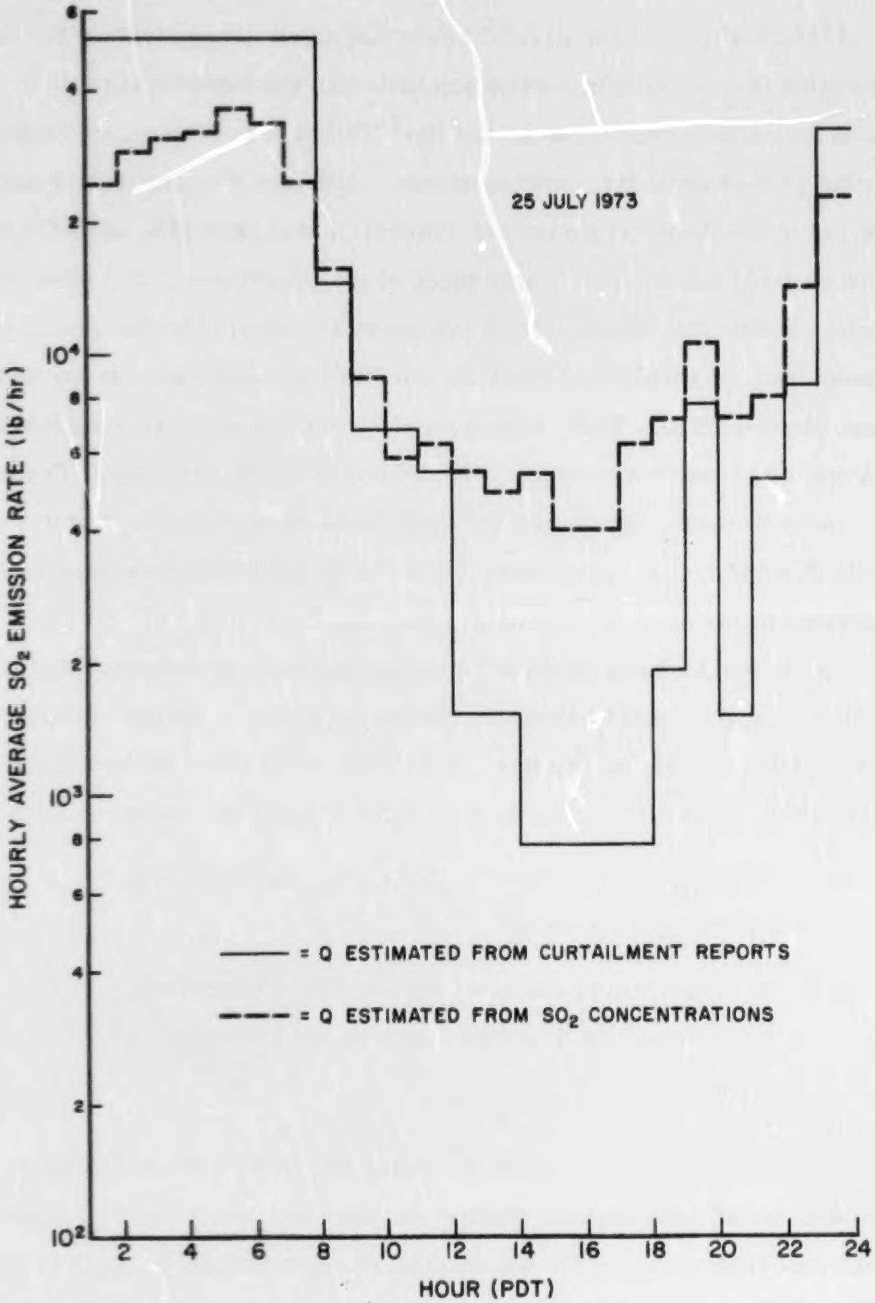

FIGURE 6-1. Comparison of hourly average SO_2 emission rates estimated from curtailment reports and from in-stack SO_2 concentration data for 25 July 1973.

Other features of the ASARCO SCS that merit discussion are the density of the existing SO_2 air quality monitoring network, the inherent time delay in implementing curtailment decisions and the effectiveness of the stack heaters in reducing ground-level SO_2 concentrations. Although air quality data are telemetered to the ASARCO Emissions Control Center from five ASARCO monitors and fourteen PSAPCA monitors, only three of the PSAPCA monitor sites (N26th and Pearl, Meeker and Maury Island) are normally affected by the ASARCO SO_2 stack emissions. ASARCO and PSAPCA monitors are collocated at the N26th and Pearl and Meeker sites. Thus, telemetered air quality data are available for only six monitor locations routinely affected by the ASARCO plume. There are sound reasons for believing that an increase in the number of SO_2 monitors, especially if additional monitors were located 1 to 2.5 kilometers south-southwest and southwest of the main stack, would result in observations of high short-term ground-level concentrations at these locations produced by low-level fugitive emissions and also by stack emissions during periods of moderate-to-strong winds. Although it is admittedly speculative, we believe an increase in the density of the existing SO_2 monitoring network along the lines outlined above would result in:

- Appropriate revisions in the current ASARCO SCS operating procedures
- A significant increase in the number of violations of the PSAPCA 5-minute and 1-hour air quality standards

The time normally required to reduce smelter stack emissions in response to a specific curtailment request appears to vary from about 10 to 30 minutes. The additional time required for the reduced stack emissions to begin to change ground-level SO_2 concentrations at the monitors depends on the wind speed, wind direction and stability conditions. This additional time delay typically varies from a minimum of 10 minutes to 1 hour or more. We conclude that the ASARCO

SCS thus has an inherent characteristic time delay of 20 minutes to 1 hour or more, which includes both the time required to implement a curtailment decision and the time required for the reduced emissions to start to affect the air quality at the SO_2 monitor sites located closest to the ASARCO smelter.

Operation of one or both of the stack heaters is an important feature of the ASARCO SCS. We have calculated the increase in plume rise resulting from the operation of the stack heaters by using the current stack and emissions data for 51-percent constant emissions control in Table 2-1 in the plume rise equations presented in Section A.2 of Appendix A. These calculations show that the use of one stack heater increases plume rise by about 14 percent and the use of two stack heaters increases plume rise by about 19 percent. To a first approximation, these percentage increases in plume rise will result in almost equivalent percentage reductions in the maximum short-term ground-level SO_2 concentrations. Specifically, the maximum short-term ground-level concentration is approximately inversely proportional to the square of the sum of the stack height and the buoyant plume rise. For mean wind speeds of 3 or 4 meters per second, the buoyant plume rise without stack heaters is approximately equivalent to the actual stack height of 172 meters (565 feet). With both stack heaters in operation, the buoyant plume rise is increased 19 percent and is thus equal to 205 meters (672 feet). By adding the stack height to the buoyant plume rise, squaring each sum and taking the ratio of the squared sums, one obtains a reduction in the maximum ground-level concentration of about 20 percent due to the operation of both stack heaters. Thus, the effect of the operation of the stack heaters on ground-level concentrations is relatively small except when the enhancement in plume rise is sufficient to cause the plume to stabilize above the top of the surface mixing layer.

6.4 EFFECTIVENESS OF THE ASARCO SCS

Since the ASARCO Tacoma SCS began operation in 1970, there has been a significant improvement in the ambient air quality at the locations of the PSAPCA and ASARCO SO_2 monitors. This improvement is illustrated by Tables 6-1 and 6-2 which show, for the period 1968 to present, the number of violations at the PSAPCA SO_2 monitor at N26th and Pearl of the National and PSAPCA ambient air quality standards, respectively. The N26th and Pearl monitor is the PSAPCA monitor most frequently affected by ASARCO emissions and it has been in operation longer than any other PSAPCA monitor. Table 6-1 shows that no violations of the 3-hour and 24-hour National standards occurred at N26th and Pearl after 1971 until the first part of 1976 when the 3-hour standard was violated. Since 1971, there have been a total of three observations (one in 1974 and two in the first part of 1976) above the 3-hour standard and one observation (in the first part of 1976) above the 24-hour standard. Table 6-2 shows that the number of violations of the PSAPCA short-term standards decreased significantly through 1973. ASARCO (Welch, 1975) attributes the majority of the 1974 violations to start-up and shake-down problems with the liquid SO_2 plant. However, the entries in Table 6-2 indicate the number of violations has remained fairly constant since 1973 and there is a good possibility that the number of violations during 1976 will exceed those for 1975 and 1974.

We believe that Tables 6-1 and 6-2 demonstrate that the ASARCO SCS reached the limit of effectiveness during 1973 and 1974 in terms of its capability to prevent violations of both the National and PSAPCA ambient air quality standards. With respect to the National standards, the effectiveness of the ASARCO SCS is very high although, as shown by the experience in early 1976, it is incapable of preventing all violations of the 3-hour and possibly the 24-hour standards. Table 6-2 shows that all of the PSAPCA short-term standards are still being violated, especially the 5-minute and 1-hour standards.

TABLE 6-1

TOTAL NUMBER OF VIOLATIONS OF THE NATIONAL AIR QUALITY STANDARDS FOR SO_2 AT N26th AND PEARL

Year	Number of Violations*	
	3-Hour Secondary Standard	24-Hour Primary Standard
1976**	1 (2)	0 (1)
1975	0 (0)	0 (0)
1974	0 (1)	0 (0)
1973	0 (0)	0 (0)
1972	0 (0)	0 (0)
1971	1 (2)	1 (2)
1970	5 (6)	1 (2)
1969	5 (6)	4 (5)
1968	0 (1)	1 (2)

*Total number of observations above the standard are enclosed by parentheses

**As of 6 February 1976

TABLE 6-2

TOTAL NUMBER OF VIOLATIONS OF THE PSAPCA AIR QUALITY STANDARDS FOR SO_2 AT N26th AND PEARL

Year	Number of Violations			
	5-Minute Standard of 1.0 ppm	1-Hour Standard of 0.40 ppm	1-Hour Standard of 0.25 ppm	24-Hour Standard of 0.10 ppm
1976*	10	10	15	2
1975	8	6	35	0
1974	10	6	21	1
1973	16	4	27	0
1972	27	11	34	0
1971	39	20	52	3
1970	169	62	140	4
1969	199	84	219	15
1968	124	56	125	10

*As of 6 February 1976

As explained in Sections 6.2 and 6.3, because of the delay time of 20 minutes to 1 hour or more inherent in the ASARCO SCS and because of the practical impossibility of anticipating all of the times that the plume will mix to the ground, it is most unlikely that any further improvement in ambient air quality can be achieved (with the present source configuration) without a substantial reduction in the maximum allowable emission rate. It is interesting in this regard to note that the addition of the liquid SO_2 plant in 1974 and the increase in the constant emissions control from 17 to 51 percent appears to have had no effect on the number of violations at the N26th and Pearl monitor of either the National or PSAPCA air quality standards. We believe a completely effective SCS would require that the smelter operate most of the time at a curtailed rate which would not differ appreciably from the constant emission rate in Section 5.3 of 2000 to 2500 pounds of SO_2 per hour given for the Control Alternatives that met the PSAPCA 1-hour standard of 0.25 ppm. Consequently, we doubt that an SCS is a viable method of maintaining the 5-minute and 1-hour PSAPCA standards for the present ASARCO smelter configuration or for any of the alternative smelter configurations (Control Alternatives) considered in this report that endanger these standards.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The principal conclusions of this study of the impact on ambient air quality of SO_2 emissions from the ASARCO-Tacoma smelter are:

1. Without the use of Supplementary Control System (SCS) techniques, SO_2 emissions from the present smelter source configuration with 51-percent constant emissions control would result in violations of all National, PSAPCA and Washington DOE short-term (5-minute, 1-hour, 3-hour and 24-hour) SO_2 air quality standards; the National, PSAPCA and Washington DOE annual standards as well as the 30-day PSAPCA standard would not be violated.

2. The percent constant emissions control required, without the use of SCS techniques, to prevent violations of the short-term air quality standards by SO_2 emissions from the ASARCO-Tacoma smelter depends on the source configuration. For the 20 hypothetical source configurations (Control Alternatives) evaluated in this study, the maximum allowable SO_2 emission rate consistent with meeting all PSAPCA and Washington DOE short-term standards varies from about 2,000 to 2,500 pounds of SO_2 per hour. Based on an assumed current average uncurtailed emission rate of 24,800 pounds of SO_2 per hour for the present 51-percent constant emissions control, the above rates of 2,000 to 2,500 pounds per hour respectively represent 96- and 95-percent constant emissions control. These maximum allowable emission rates will also ensure compliance with all National SO_2 air quality standards.

3. Our evaluation of the effectiveness of the ASARCO SCS in meeting the National short-term SO_2 air quality standards, which is supported by air quality observations from the PSAPCA monitors, shows that it is capable of preventing

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most violations of the National 3-hour and 24-hour standards. In part, the past success of the ASARCO SCS in meeting the National short-term standards is attributable to the stack heater operations and emissions curtailment activities arising from attempts to meet the more stringent PSAPCA short-term standards.

4. Our evaluation of the effectiveness of the ASARCO SCS in meeting the PSAPCA and Washington DOE short-term air quality standards, which is also supported by air quality observations from the PSAPCA monitors, shows that it is not a viable means of preventing violations of these standards, especially the 5-minute and 1-hour standards. The fundamental difficulty in relying on SCS techniques to meet these standards is the minimum delay of 20 minutes to 1 hour or longer inherent in the ASARCO SCS from the time a curtailment decision is made until the time that the implemented curtailment decision can significantly affect the air quality at the closest SO_2 monitors. This means that curtailment decisions cannot be made on the basis of telemetered data from the air quality monitors but must instead always be made, using meteorological forecasting techniques, at least 20 minutes to 1 hour in advance of any occurrence of high ground-level SO_2 concentrations. Given the large percentage curtailment required (40 to 90 percent of the average uncurtailed emission rate for full production with 51-percent constant emissions control) and the large uncertainties inherent in meteorological predictions, we believe it clearly impossible for ASARCO to achieve the nearly-perfect forecasting capability required in using any SCS techniques to prevent violations of the 5-minute and 1-hour PSAPCA standards.

5. For the reasons outlined above, we believe that the only way in which the PSAPCA 5-minute and 1-hour SO_2 standards can be met with the present source configuration is to limit the maximum stack emission rate to about 2,500 pounds of SO_2 per hour, which is approximately equivalent to the maximum allowable constant emission rate for the Control Alternatives that meet all the National, PSAPCA and Washington DOE air quality standards for SO_2.

7.2 RECOMMENDATIONS

During our study of the air quality impact of SO_2 emissions from ASARCO and other major SO_2 sources in the Seattle-Tacoma area, we identified three problem areas that we believe require further investigation and/or action. We therefore recommend that:

1. The air quality impact of low-level fugitive SO_2 emissions from the ASARCO smelter as well as the impact of possible downwash effects from the main ASARCO stack should be further investigated by placing additional SO_2 monitors closer to the smelter than the existing monitors. The existing PSAPCA and ASARCO SO_2 monitors are located too far from the smelter to detect these effects. The EPA SO_2 monitor that was located approximately 1.2 kilometers south-southwest of the main stack from 18 September 1975 through 27 January 1976 (see Appendix D) measured high hourly SO_2 concentrations. However, from the available emissions and meteorological data, we are not able to isolate the contributions of low-level fugitive emissions and stack downwash effects to these observations.

2. The smelter operation reports submitted by ASARCO to PSAPCA should include hourly average values of stack exit temperature, actual stack volumetric flow rate, in-stack SO_2 concentration and the stack SO_2 emission rate in pounds per hour. If possible, the curtailment requests should be reported in terms of maximum allowable SO_2 emission rates in pounds of SO_2 per hour or in terms that can easily be converted to emission rates in pounds of SO_2 per hour by regulatory agency personnel.

3. The air quality impact of low-level SO_2 emissions from the Kaiser Aluminum Plant in Tacoma should be investigated by diffusion modeling and/or air quality monitoring to determine whether emissions from this source are endangering the National and PSAPCA air quality standards. Diffusion-model

calculations made during this study indicate that emissions from Kaiser Aluminum may be endangering these standards. A detailed investigation of the air quality impact of SO_2 emissions from Kaiser Aluminum was beyond the scope of the present study.

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APPENDIX A

MATHEMATICAL MODELS USED TO CALCULATE GROUND-LEVEL CONCENTRATIONS

A.1 INTRODUCTION

The computerized diffusion models described in this appendix fall into two general categories: (1) Short-term models for calculating time-averaged ground-level concentrations for averaging times of 1, 3, 8 and 24 hours; (2) Long-term models for calculating seasonal and annual ground-level concentrations. Both the short-term and long-term concentration models are modified versions of the Gaussian plume model for continuous sources described by Pasquill (1962). In the short-term model, the plume is assumed to have Gaussian vertical and lateral concentration distributions. The long-term model is a sector model similar in form to the Environmental Protection Agency's Climatological Dispersion Model (Calder, 1971) in which the vertical concentration distribution is assumed to be Gaussian and the lateral concentration distribution within a sector is rectangular (a smoothing function is used to eliminate sharp discontinuities at the sector boundaries). The σ_z vertical expansion curves and the σ_y lateral expansion curves are determined by using turbulent intensities in simple power-law expressions that include the effects of initial source dimensions. In both the short-term and long-term models, buoyant plume rise is calculated by means of the Briggs (1971) plume-rise formulas. An exponent law is used to adjust the surface wind speed to the source height for plume-rise calculations and to the plume stabilization height for concentration calculations. Both the short-term and the long-term models contain provisions to account for the effects of complex terrain.

Table A-1 lists the hourly meteorological inputs required by the short-term concentration model. Lateral and vertical turbulent intensities σ'_A and σ'_E

TABLE A-1

HOURLY METEOROLOGICAL INPUTS REQUIRED BY THE SHORT-TERM CONCENTRATION MODEL

Parameter	Definition
$\bar{u}_R$	Mean wind speed at height z_R
θ	Mean wind direction at height z_R
p	Wind-profile exponent
σ'_A	Wind azimuth-angle standard deviation in radians
σ'_E	Wind elevation-angle standard deviation in radians
T_a	Ambient air temperature (^oK)
H_m	Depth of surface mixing layer
$\frac{\partial \theta}{\partial z}$	Vertical potential temperature gradient

may be directly specified or may be assigned on the basis of the Pasquill stability category. The Pasquill stability category is determined from surface weather observations using the Turner (1964) wind-speed and solar-index values. Mixing depths may be obtained from rawinsonde or pibal measurements, or they may be assigned on the basis of tabulations of the frequency of occurrence of wind speed and mixing depth (available from the National Climatic Center for synoptic rawinsonde stations). Potential temperature gradients may be measured or assigned on the basis of climatology.

Table A-2 lists the meteorological inputs required by the long-term concentration model. Joint-frequency distributions of wind-speed and wind-direction categories according to the Pasquill stability categories may be obtained from the National Climatic Center. Alternately, surface wind observations may be analyzed to generate wind-frequency distributions by time-of-day categories (night, morning, afternoon and evening). Vertical turbulent intensities may be determined from a climatology of actual measurements or may be assigned on the basis of the Pasquill stability categories. Median mixing depths may be determined from the seasonal tabulations of the frequency of occurrence of wind speed and mixing depth. Vertical potential temperature gradients may be assigned to stability or time-of-day categories on the basis of climatology.

A.2 PLUME-RISE FORMULAS

The effective stack height H of a buoyant plume is given by the sum of the physical stack height h and the buoyant rise Δh. For an adiabatic or unstable atmosphere, the buoyant rise Δh_N is given by

$$\Delta h_N = \left[\frac{1}{\bar{u}\{h\}} \left(\frac{3F}{2\gamma_1^2} \right)^{1/3} (10h)^{2/3} \right] f \qquad \text{(A-1)}$$

TABLE A-2

METEOROLOGICAL INPUTS REQUIRED BY THE LONG-TERM CONCENTRATION MODEL

Parameter	Definition
$f_{i,j,k,\ell}$ (Table)	Frequency distribution of wind-speed and wind-direction categories by stability or time-of-day categories for the ℓ^{th} season
z_R	Height at which wind-frequency distributions were obtained
$p_{k,i}$ (Table)	Wind-profile exponents for each stability or time-of-day category and i^{th} wind-speed category
$\sigma'_{E;i,k}$ (Table)	Standard deviation of the wind-elevation angle in radians for the i^{th} wind-speed category and k^{th} stability or time-of-day category
$T_{a;k,\ell}$ (Table)	Ambient air temperature for the k^{th} stability or time-of-day category and ℓ^{th} season
$\left(\frac{\partial\theta}{\partial z}\right)_{i,k}$ (Table)	Vertical potential temperature gradient for the i^{th} wind-speed category and k^{th} stability or time-of-day category
$H_{m;i,k,\ell}$ (Table)	Median surface mixing depth for the i^{th} wind-speed category, k^{th} stability or time-of-day category and ℓ^{th} season
$\bar{u}\{z_R\}_i$ (Table)	Mean wind speeds at height z_R

where the expression in the brackets is from Briggs (1971; 1972) and

$\bar{u}\{h\}$ = the mean wind speed at the stack height h

γ_1 = the adiabatic entrainment coefficient ~ 0.6

F = the initial buoyancy flux

$$= \frac{gV}{\pi}\left(1 - \frac{T_a}{T_s}\right) \tag{A-2}$$

V = the volumetric emission rate of the stack

$= \pi\, r^2\, w$

r = inner radius of stack

w = stack exit velocity

g = the acceleration due to gravity

T_a = the ambient air temperature (°K)

T_s = the stack exit temperature (°K)

The factor f, which limits the plume rise as the mean wind speed at stack height approaches or exceeds the stack exit velocity, is defined by

$$f = \left\{\begin{array}{cl} 1 & ;\ \bar{u}\{h\} \le w/1.5 \\ \left(\dfrac{3w - 3\bar{u}\{h\}}{w}\right) & ;\ w/1.5 < \bar{u}\{h\} < w \\ 0 & ;\ \bar{u}\{h\} \ge w \end{array}\right\} \tag{A-3}$$

The empirical correction factor f is generally not applied to stacks with Froude numbers less than about unity. The corresponding Briggs (1971) rise formula for a stable atmosphere (potential temperature gradient greater than zero) is

$$\Delta h_S = \left\{ \begin{array}{ll} \left[\dfrac{6F}{\bar{u}\{h\}\ \gamma_2^{\ 2}\ S} \right]^{1/3} & ;\ \pi\ \bar{u}\{h\}\ S^{-1/2} < 10h \\ \left[\dfrac{3F}{\bar{u}\{h\}\ \gamma_2^{\ 2}\ S} \left(1 - \cos \left(\dfrac{10S^{1/2}\ h}{\bar{u}\{h\}} \right) \right) \right]^{1/3} & ;\ \pi\ \bar{u}\{h\}\ S^{-1/2} \geq 10h \end{array} \right\} f \qquad \text{(A-4)}$$

where

γ_2 = the stable entrainment coefficient ~ 0.66

$S = \dfrac{g}{T_a} \dfrac{\partial \theta}{\partial z}$

$\dfrac{\partial \theta}{\partial z}$ = vertical potential temperature gradient

The entrainment coefficients γ_1 and γ_2 are based on the suggestions of Briggs (1972). It should be noted that Equation (A-4) does not permit the calculated stable rise Δh_s to exceed the adiabatic rise Δh_N as the atmosphere approaches a neutral stratification ($\partial\theta/\partial z$ approaches 0). A procedure of this type is recommended by Briggs (1972).

A.3 SHORT-TERM CONCENTRATION MODEL

A.3.1 Elevated Sources

The atmospheric dispersion model used to calculate hourly average ground-level concentrations downwind from an elevated continuous source is given by

$$\chi\{x, y\} = \frac{K\ Q}{\pi\ \bar{u}\{H\}\ \sigma_y\ \sigma_z} \{\text{Vertical Term}\}\ \{\text{Lateral Term}\}\ \{\text{Decay Term}\} \qquad \text{(A-5)}$$

where

K = scaling coefficient to convert input parameters to dimensionally consistent units

Q = source emission rate

$\bar{u}\{H\}$ = mean wind speed at the plume stabilization height H

σ_y, σ_z = standard deviations of the lateral and vertical concentration distributions at downwind distance x

The Vertical Term refers to the plume expansion in the vertical or z direction and includes a multiple reflection term that limits cloud growth to the surface mixing layer.

$$\{\text{Vertical Term}\} = \left\{ \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] + \sum_{n=1}^{\infty}\left[\exp\left[-\frac{1}{2}\left(\frac{2n\,H_m + H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{2n\,H_m - H}{\sigma_z}\right)^2\right]\right]\right\} \tag{A-6}$$

where H_m is the depth of the surface mixing layer. The exponential terms in the infinite series in Equation (A-6) rapidly approach zero near the source. At the downwind distance where the exponential terms are non-zero for n equal 3, the plume has become approximately uniformly mixed within the surface mixing layer. In order to shorten computer computation time, Equation (A-6) is changed to the form

$$\{\text{Vertical Term}\} = \frac{\sqrt{2\pi}\,\sigma_z}{2H_m} \tag{A-7}$$

beyond this point. Equation (A-7) changes the form of the vertical concentration distribution from Gaussian to rectangular. If H exceeds H_m, the vertical term is set equal to zero which results in a zero value for the ground-level concentration.

The **Lateral Term** refers to the crosswind expansion of the plume and is given by the expression

$$\{\text{Lateral Term}\} = \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \tag{A-8}$$

where y is the crosswind distance from the plume centerline to the point at which concentration is calculated.

The **Decay Term**, which accounts for the possibility of pollutant removal by physical or chemical processes, is of the form

$$\{\text{Decay Term}\} = \exp\left[-\psi\, x/\bar{u}\{H\}\right] \tag{A-9}$$

where

ψ = the washout coefficient Λ (sec^{-1}) for precipitation scavenging

= $\frac{0.692}{T_{1/2}}$, where $T_{1/2}$ is the pollutant half life for physical or chemical removal

= 0 for no depletion (ψ is automatically set to zero by the computer program unless otherwise specified)

In the model calculations, the observed mean wind speed $\bar{u}_R$ is adjusted from the measurement height z_R to the source height h for plume-rise calculations and to the stabilization height H for the concentration calculations by a wind-profile exponent law

$$\bar{u}\{z\} = \bar{u}\{z_R\}\left(\frac{z}{z_R}\right)^p \tag{A-10}$$

The exponent p, which is assigned on the basis of atmospheric stability, ranges from about 0.1 for very unstable conditions to about 0.4 for very stable conditions.

According to the derivation in the report by Cramer, et al. (1972), the standard deviation of the lateral concentration distribution σ_y is given by the expression

$$\sigma_y\{x\} = \sigma'_A x_{ry} \left[\frac{x + x_y - x_{ry}(1-\alpha)}{\alpha x_{ry}}\right]^{\alpha} \tag{A-11}$$

$$x_y = \left\{ \begin{array}{ll} \dfrac{\sigma_{yR}}{\sigma'_A} - x_R & ; \quad \dfrac{\sigma_{yR}}{\sigma'_A} \leq x_{ry} \\ \alpha x_{ry} \left(\dfrac{\sigma_{yR}}{x_{ry}\,\sigma'_A}\right)^{1/\alpha} - x_R + x_{ry}(1-\alpha) & ; \quad \dfrac{\sigma_{yR}}{\sigma'_A} > x_{ry} \end{array} \right\} \tag{A-12}$$

where

σ'_A = the standard deviation of the wind-azimuth angle in radians

x_{ry} = distance over which rectilinear plume expansion occurs downwind from an ideal point source (~ 50 meters)

σ_{yR} = the standard deviation of the lateral concentration distribution at downwind distance x_R

α = the lateral diffusion coefficient (~ 0.9)

The virtual distance x_y is not permitted to be less than zero. The lateral turbulent intensity σ'_A may be specified directly or may be assigned on the basis of the Pasquill stability category.

Following the derivation of Cramer, et al. (1972) and setting the vertical diffusion coefficient β equal to unity, the standard deviation of the vertical concentration distribution σ_z is given by the expression

$$\sigma_z\{x\} = \sigma'_E\left(x + x_z\right) \tag{A-13}$$

$$x_z = \left\{\begin{array}{ll} \dfrac{\sigma_{zR}}{\sigma'_E} - x_R & ; \dfrac{\sigma_{zR}}{\sigma'_E} \geq x_R \\ \\ 0 & ; \dfrac{\sigma_{zR}}{\sigma'_E} < x_R \end{array}\right\} \tag{A-14}$$

where

σ'_E = standard deviation of the wind-elevation angle in radians

σ_{zR} = the standard deviation of the vertical concentration distribution at downwind distance x_R

The vertical turbulent intensity σ'_E may also be obtained from direct measurements or may be assigned according to the Pasquill stability categories. When σ'_E values corresponding to the Pasquill stability categories are entered in Equation (A-13), the resulting curves will differ from the corresponding Pasquill-Gifford curves in that Equation (A-13) assumes rectilinear expansion at all downwind distances. Thus, σ_z values obtained from Equation (A-13) will be smaller than the values obtained from the Pasquill-Gifford A and B curves and larger than the values obtained from the D, E and F curves at long downwind distances. However, the multiple reflection term in Equation (A-6) which confines the plume to the surface mixing layer accounts for the behavior of the D, E and F curves (decrease in the expansion rate with distance) in a manner that may be related to the meteorology of the area.

Following the recommendations of Briggs (1972), the lateral and vertical standard deviations of a stabilized buoyant plume are defined by

$$\sigma_{yR} = \sigma_{zR} = \frac{0.5\ \Delta h}{2.15} \tag{A-15}$$

The downwind distance to stabilization x_R is given by

$$x_R = \left\{ \begin{array}{ll} 10h & ; \ \frac{\partial \theta}{\partial z} \leq 0 \\ \pi \, \bar{u}\{h\} \, S^{-1/2} & ; \ \frac{\partial \theta}{\partial z} > 0 \text{ and } \pi \, \bar{u}\{h\} \, S^{-1/2} < 10h \\ 10h & ; \ \frac{\partial \theta}{\partial z} > 0 \text{ and } \pi \, \bar{u} \, h \ S^{-1/2} \geq 10h \end{array} \right\} \qquad \text{(A-16)}$$

A. 3. 2 Application of the Short-Term Model to Low-Level Emissions

The short-term diffusion model in Section A. 3. 1 may be used to calculate ground-level concentrations resulting from low-level emissions such as losses through building vents. These emissions are rapidly distributed by the cavity circulation of the building wake and quickly assume the dimensions of the building. Ground-level concentrations are calculated by setting the release height h and the buoyancy parameter F equal to zero. The standard deviation of the lateral concentration distribution at the source σ_{yo} is defined by the building crosswind dimension y_o divided by 4. 3. The standard deviation of the vertical concentration distribution at the source σ_{zo} is obtained by dividing the building height by 2. 15. The initial dimensions σ_{yo} and σ_{zo} are assumed to be applicable at the downwind edge of the building. It should be noted that separate turbulent intensities σ'_A and σ'_E may be defined for the low-level sources to account for the effects of surface roughness elements and heat sources.

A. 3. 3 Short-Term Concentration Model for Area Sources

The atmospheric dispersion model used to calculate ground-level concentrations at downwind distance x from the downwind edge of an area source is given by the expression

$$\chi\{x > x_o, y\} = \frac{K\,Q}{\sqrt{2\pi}\; u\{h\}\; \sigma_z\{x\}\; y_o}\,\{\text{Vertical Term}\}\;\{\text{Lateral Term}\}\;\{\text{Decay Term}\} \qquad \text{(A-17)}$$

where

Q = area source strength in units of mass per unit time

y_o = crosswind source dimension

$$\sigma_z\{x\} = \begin{cases} \dfrac{\sigma'_E\, x_o}{\ln\left[\dfrac{\sigma'_E(x+x_o)+h}{\sigma'_E(x)+h}\right]} & ;\; x < 3\,x_o \\[2ex] \sigma'_E(x+x_o/2)+h & ;\; x \ge 3\,x_o \end{cases} \qquad \text{(A-18)}$$

x_o = alongwind dimension of the area source

h = the characteristic height of the area source

The Vertical Term for an area source is given by

$$\{\text{Vertical Term}\} = \begin{cases} 1+2\displaystyle\sum_{n=1}^{3}\left\{\exp\left[-\frac{1}{2}\left(\frac{2n\,H_m}{\sigma_z\{x\}}\right)^2\right]\right\} & ;\; \exp\left[-\dfrac{1}{2}\left(\dfrac{6H_m}{\sigma_z}\right)^2\right] = 0 \\[3ex] \dfrac{\sqrt{2\pi}\;\sigma_z\{x\}}{2\,H_m} & ;\; \exp\left[-\dfrac{1}{2}\left(\dfrac{6H_m}{\sigma_z}\right)^2\right] > 0 \end{cases} \qquad \text{(A-19)}$$

The Lateral Term is given by the expression

$$\{\text{Lateral Term}\} = \left\{ \text{erf}\left[\frac{y_o/2 + y}{\sqrt{2}\ \sigma_y\{x\}}\right] + \text{erf}\left[\frac{y_o/2 - y}{\sqrt{2}\ \sigma_y\{x\}}\right] \right\} \tag{A-20}$$

where

y_o = crosswind dimension of the area source
y = crosswind distance from the centerline of the area source

and

$$\sigma_y\{x\} = \sigma'_A(x + x_o/2) \tag{A-21}$$

The Decay Term is given by Equation (A-9) above.

The concentration at points interior to the area source is given by

$$\chi\{x'\} = \frac{2\,K\,Q}{\sqrt{2\pi}\ u\{h\}\ x_o\ y_o\ \sigma'_E} \left\{ \ln\left[\frac{\sigma'_E(x' + 1) + h}{\sigma'_E + h}\right] \right\} \{\text{Vertical Term}\} \tag{A-22}$$

where

x' = distance downwind from the upwind edge of the area source

A.4 LONG-TERM CONCENTRATION MODEL

A.4.1 Elevated Sources

The atmospheric dispersion model for elevated point and volume sources is similar in form to the Air Quality Display Model (Environmental Protection Agency, 1969) and the Climatological Dispersion Model (Calder, 1971). In the model, the area surrounding a continuous source of pollutants is divided into sectors of equal angular width corresponding to the class intervals of the seasonal and annual frequency distributions of wind direction. The emission rate during a season or year is partitioned according to the relative wind-direction frequencies. Ground-level concentration fields for each source are translated to a common reference coordinate grid system and summed to obtain the total due to all emissions. For a single source, the mean seasonal concentration at a point (r, θ) is given by

$$\chi_{\ell}\{r,\theta\} = \frac{2\,K\,Q}{\sqrt{2\pi}\; r\;\Delta\theta'} \sum_{i,j,k} \left[\frac{f_{i,j,k,\ell}}{\bar{u}_i\{H_{i,k,\ell}\}\;\sigma_{z;i,k,\ell}} \; S\{\theta\}\;\; V_{i,k,\ell} \right. \tag{A-23}$$

$$\left. \exp\left[-\psi\, r/\bar{u}_i\{H_{i,k,\ell}\}\right] \right]$$

$$V_{i,k,\ell} = \exp\left[-\frac{1}{2}\left(\frac{H_{i,k,\ell}}{\sigma_{z;i,k,\ell}}\right)^2\right] + \sum_{n=1}^{\infty} \left\{ \exp\left[-\frac{1}{2}\left(\frac{2n\,H_{m;i,k,\ell} - H_{i,k,\ell}}{\sigma_{z;i,k,\ell}}\right)^2\right] \right. \tag{A-24}$$

$$\left. + \exp\left[-\frac{1}{2}\left(\frac{2n\,H_{m;i,k,\ell} + H_{i,k,\ell}}{\sigma_{z;i,k,\ell}}\right)^2\right] \right\}$$

where

$f_{i,j,k,\ell}$ = frequency of occurrence of the i^{th} wind-speed category, j^{th} wind-direction category and k^{th} stability or time-of-day category for the ℓ^{th} season

$\Delta\theta'$ = the sector width in radians

$S\{\theta\}$ = a smoothing function

$$S\{\theta\} = \begin{cases} \dfrac{\Delta\theta' - \left|\theta'_j - \theta'\right|}{\Delta\theta'} & ; \quad \left|\theta'_j - \theta'\right| \le \Delta\theta' \\ 0 & ; \quad \left|\theta'_j - \theta'\right| > \Delta\theta' \end{cases} \tag{A-25}$$

θ'_j = the angle measured in radians from north to the centerline of the j^{th} wind-direction sector

θ' = the angle measured in radians from north to the point (r, θ)

As with the short-term model, the Vertical Term given by Equation (A-24) is changed to the form

$$V_{i,k,\ell} = \frac{\sqrt{2\pi}\,\sigma_{z;i,k,\ell}}{2H_{m;i,k,\ell}} \tag{A-26}$$

when the exponential terms in Equation (A-24) become non-zero for n equal 3. The remaining terms in Equations (A-23) and (A-24) are identical to those previously defined in Section A. 3. 1 for the short-term model, except that the turbulent intensities and potential temperature gradients may be separately assigned to each wind-speed and/or stability (or time-of-day) category; the ambient air temperatures may be separately assigned to each stability (or time-of-day) category for each season; and the surface mixing depths may be separately assigned to each wind-speed and/or stability (or time-of-day) category for each season.

As shown by Equation (A-25), the rectangular concentration distribution within a given angular sector is modified by the function $S\{\theta\}$ which smoothes discontinuities in the concentration at the boundaries of adjacent sectors. The centerline concentration in each sector is unaffected by contributions from adjacent sectors. At points off the sector centerline, the concentration is a weighted function of the concentration at the centerline of the sector in which the calculation is being made and the concentration at the centerline of the nearest adjoining sector.

The mean annual concentration at the point (r, θ) is calculated from the seasonal concentrations using the expression

$$\chi_a\{r, \theta\} = \frac{1}{4} \sum_{\ell} \chi_{\ell}\{r, \theta\} \tag{A-27}$$

A.4.2 Application of the Long-Term Model to Low-Level Emissions

Long-term ground-level concentrations produced by low-level emissions are calculated from Equation (A-23) by setting the source height h and the buoyancy parameter F equal to zero. The standard deviation of the vertical concentration distribution at the downwind edge of the building σ_{zo} is defined as the building height divided by 2.15. Separate vertical turbulent intensities σ_E' may be defined for the low-level sources to account for the effects of surface heat sources and roughness elements. A virtual point source is used to account for the initial lateral dimension of the source in a manner identical to that described below for area sources.

A.4.3 Long-Term Concentration Model for Area Sources

The mean seasonal concentration at downwind distance r with respect to the center of an area source is given by the expression

$$\chi_\ell\{r > r_o\} = \frac{2KQ}{\sqrt{2\pi}\,R\,\Delta\theta}\left\{\sum_{i,j,k}\left[\frac{f_{i,j,k,\ell}}{\bar{u}_i\{h\}\ {}_{z;i,k}}\ S\{\theta\}\ V_{i,k,\ell}\right]\right\} \tag{A-28}$$

$$\exp\left[-\psi(r' - r_o)/\bar{u}_i\{h\}\right]$$

where

R = radial distance from the virtual point source to the receptor

$= \left(\left(r' + x_y\right)^2 + y^2\right)^{1/2}$

r' = distance from source center to receptor, measured along the plume axis

r_o = effective source radius

y = lateral distance from the cloud axis to the receptor

x_y = virtual distance

$$= r_o \cot \frac{\Delta\theta'}{2} \tag{A-29}$$

$$\sigma_{z;i,k} = \left\{\begin{array}{ll} \dfrac{2\sigma'_{E;i,k}\, r_o}{\ln\left[\dfrac{\sigma'_{E;i,k}\left(r' + r_o\right) + h}{\sigma'_{E;i,k}\left(r' - r_o\right) + h}\right]} & ; \quad r_o < r' < 6r_o \\ & \\ \sigma'_{E;i,k}\, r' + h & ; \quad r' \ge 6r_o \end{array}\right\} \tag{A-30}$$

$$V_{i,k,\ell} = \left\{ \begin{array}{ll} 1 + 2 \sum_{n=1}^{3} \exp\left[- \frac{1}{2} \left(\frac{2n\, H_{m;i,k,\ell}}{\sigma_{z;i,k}} \right)^2 \right] & ;\ \exp\left[- \frac{1}{2} \left(\frac{6H_{m;i,k,\ell}}{\sigma_{z;i,k}} \right)^2 \right] = 0 \\ \frac{\sqrt{2\pi}\ \sigma_{z;i,k}}{2H_{m;i,k,\ell}} & ;\ \exp\left[- \frac{1}{2} \left(\frac{6H_{m;i,k,\ell}}{\sigma_{z;i,k}} \right)^2 \right] > 0 \end{array} \right\} \quad \text{(A-31)}$$

and the remaining parameters are identical to those previously defined.

For points interior to the area source, the concentration for seasonal models is given by the expression

$$\chi_{\ell}\{r \leq r_o\} = \frac{2\,K\,Q}{\sqrt{2\pi}\ x_o\, y_o} \sum_{i,j,k} \left[\frac{f_{i,j,k,\ell}}{\bar{u}_i\{h\}\ \sigma'_{E;i,k}}\ \ln \left[\frac{\sigma'_{E;i,k}(r'' + 1) + h}{\sigma'_{E;i,k} + h} \right] V_{i,k,\ell} \right] \quad \text{(A-32)}$$

where

r'' = the downwind distance, measured along the plume axis from the upwind edge of the area source

A.5 APPLICATION OF THE SHORT-TERM AND LONG-TERM CONCENTRATION MODELS IN COMPLEX TERRAIN

The short-term and long-term concentration models described in Sections A.3 and A.4 are strictly applicable only for flat terrain where the base of the stack (or the building source) and the ground surface downwind from the source are at the same elevation. However, both models may also be applied to complex terrain by defining effective stabilization heights and mixing depths. The following assumptions are made in the model calculations for complex terrain:

- The top of the surface mixing layer extends over the calculation grid at a constant height above mean sea level

- Ground-level concentrations at all grid points above the top of the surface mixing layer are zero

- Plumes that stabilize above the top of the surface mixing layer do not contribute to ground-level concentrations at any grid point (this assumption also applies to flat terrain)

In order to determine whether the stabilized plume is contained within the surface mixing layer, it is necessary to calculate the mixing depth $H_m^*\{z_s\}$ at the source from the relationship

$$H_m^*\{z_s\} = \left(H_m + z_a - z_s\right) \tag{A-33}$$

where

H_m = the depth of the surface mixing layer measured at a point with elevation z_a above mean sea level

z_s = the height above mean sea level of the source

Equation (A-33) is represented schematically in Figure A-1. As shown by the figure, the actual top of the surface mixing layer is assumed to remain at a constant elevation above mean sea level. If the height H of the stabilized plume above the base of the stack is less than or equal to $H_m^*\{z_s\}$, the plume is defined to be contained within the surface mixing layer.

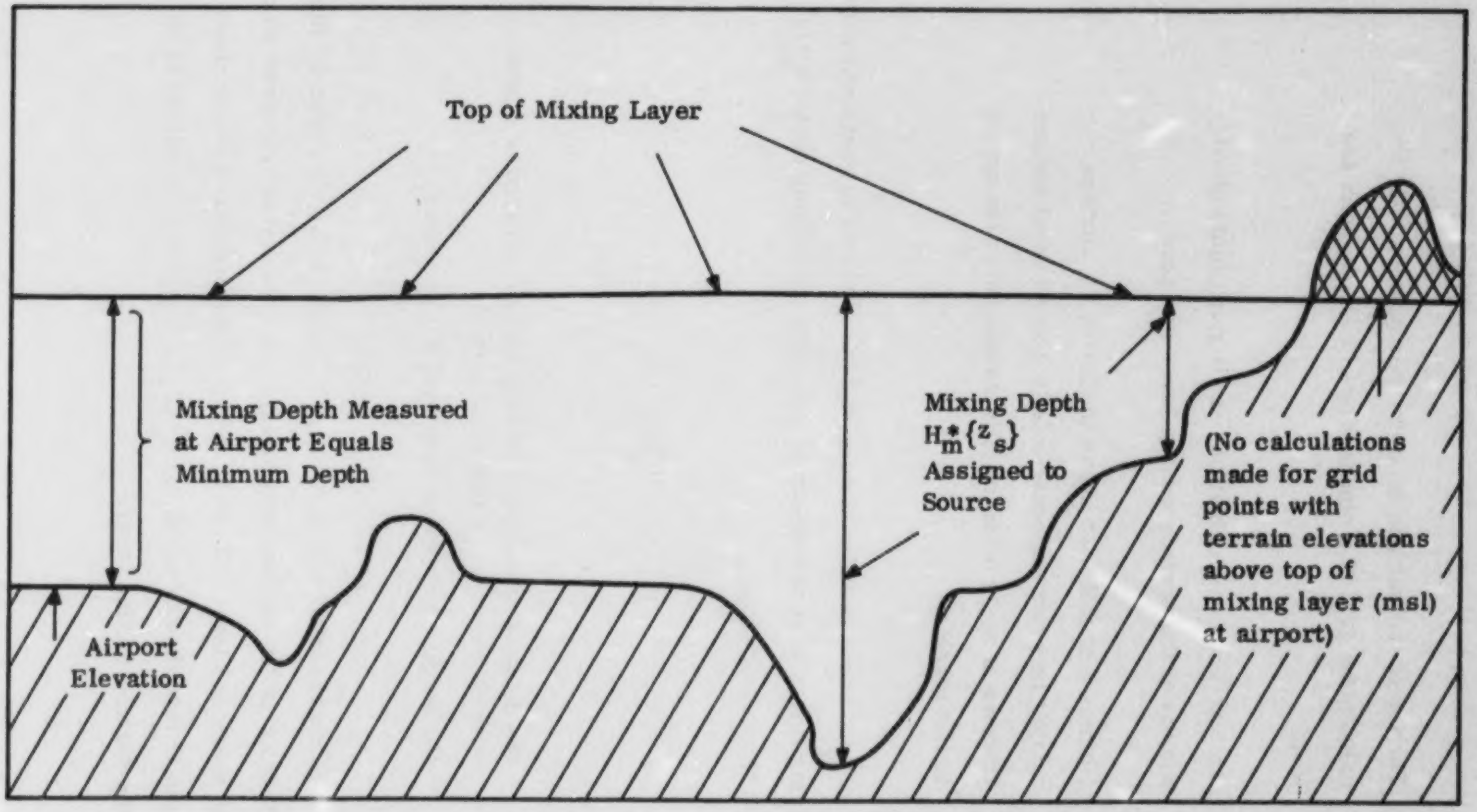
Top of Mixing Layer
Mixing Depth Measured at Airport Equals Minimum Depth
Airport Elevation
Mixing Depth $H_m^*\{z_s\}$ Assigned to Source
(No calculations made for grid points with terrain elevations above top of mixing layer (msl) at airport)

FIGURE A-1. Mixing depth $H_m^*\{z_s\}$ used to determine whether the stabilized plume is contained within the surface mixing layer.

The height H_o of the stabilized plume above mean sea level is given by the sum of the height H of the stabilized plume above the base of the stack and the elevation z_s of the base of the stack. At any elevation z above mean sea level, the effective height $H'\{z\}$ of the plume centerline above the terrain is then given by

$$H'\{z\} = \left\{ \begin{array}{ll} H_o - z & ; \; H_o - z \geq 0 \\ 0 & ; \; H_o - z < 0 \end{array} \right\} \qquad \text{(A-34)}$$

For building sources, $H'\{z\}$ is always set equal to zero.

The effective mixing depth $H'_m\{z\}$ above a point at elevation z above mean sea level is defined by

$$H'_m\{z\} = \left\{ \begin{array}{ll} H_m & ; \; z \geq z_a \\ H_m + z_a - z & ; \; z < z_a \end{array} \right\} \qquad \text{(A-35)}$$

Figure A-2 illustrates the assumptions implicit in Equation (A-35). For grid points at elevations below the airport elevation, the effective mixing depth $H'_m\{z\}$ is allowed to increase in a manner consistent with Figure A-1. However, in order to prevent a physically unrealistic compression of plumes as they pass over elevated terrain, the effective mixing depth is not permitted to be less than the mixing depth measured at the airport. It should be noted that the concentration is set equal to zero for grid points above the actual top of the mixing layer (see Figure A-1).

The terrain adjustment procedures also assume that the mean wind speed at any given height above sea level is constant. Thus, the wind speed $\bar{u}_R$ measured at height z_R above the surface at a point with elevation z_a above mean

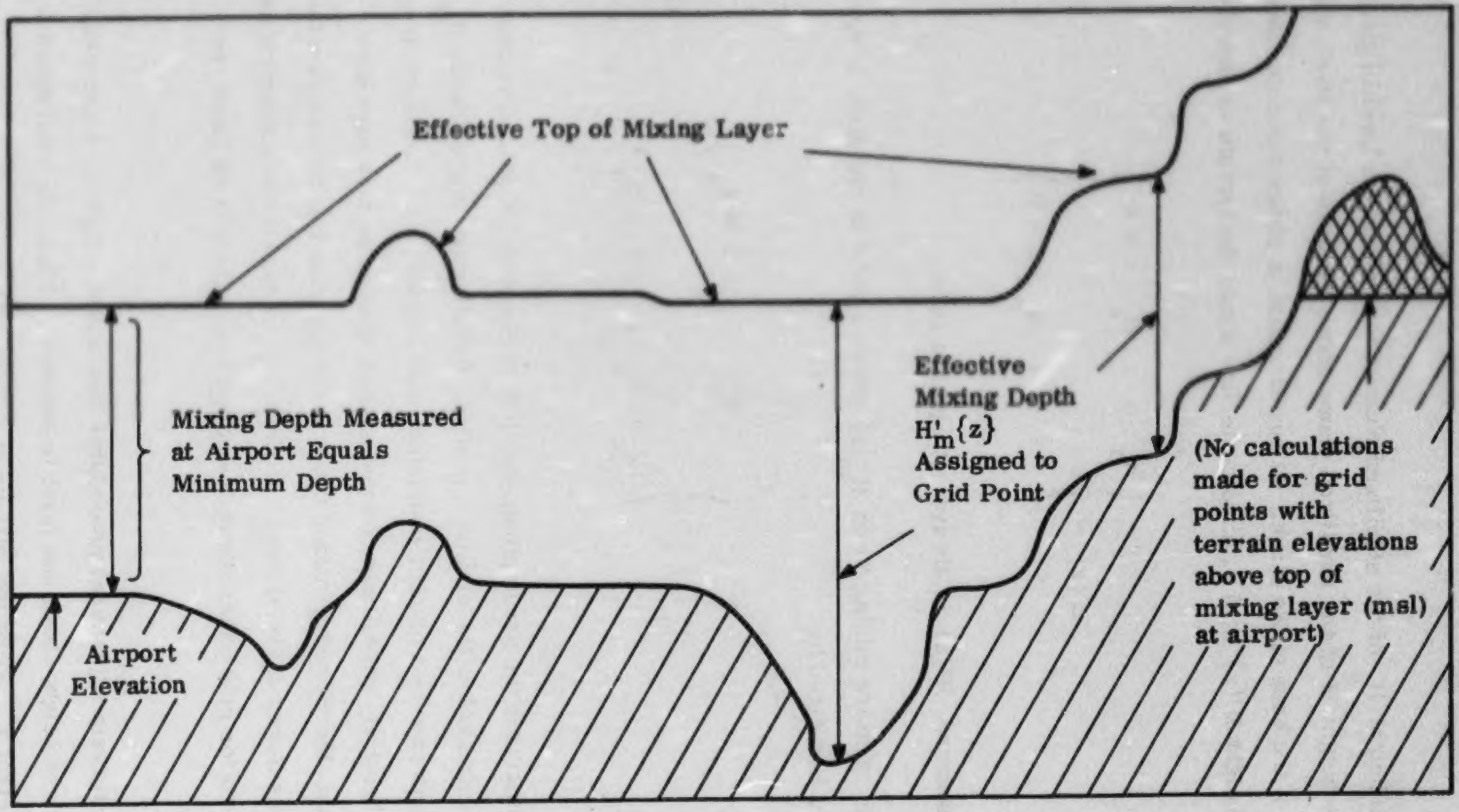
Effective Top of Mixing Layer
Mixing Depth Measured at Airport Equals Minimum Depth
Effective Mixing Depth $H'_m\{z\}$ Assigned to Grid Point
(No calculations made for grid points with terrain elevations above top of mixing layer (msl) at airport)
Airport Elevation

FIGURE A-2. Effective mixing depth $H'_m\{z\}$ assigned to grid points for the concentration calculations.

sea level is adjusted to the stack height for the plume-rise calculations by the relationship

$$\bar{u}\{h\} = \begin{cases} \bar{u}_R \left(\dfrac{h_o - z_a}{z_R} \right)^p & ; \quad h_o \geq z_a + z_R \\ \\ \bar{u}_R & ; \quad h_o < z_a + z_R \end{cases} \tag{A-36}$$

where h_o is the height above mean sea level of the top of the stack. Similarly, the wind speed $\bar{u}\{H\}$ used in the concentration calculations is given by

$$\bar{u}\{H\} = \begin{cases} \bar{u}_R \left(\dfrac{H_o - z_a}{z_R} \right)^p & ; \quad H_o \geq z_a + z_R \\ \\ \bar{u}_R & ; \quad H_o < z_a + z_R \end{cases} \tag{A-37}$$

It should be noted that the terrain-adjustment procedures outlined above provide a very simple representation of complex plume-terrain interactions that are not yet well understood. Because the model assumptions are generally conservative, it is possible that concentrations calculated for elevated terrain, especially elevated terrain near a source, exceed the concentrations that actually occur. It should also be noted that the procedures described above differ from previous "terrain-intersection" models in that terrain intersection is only permitted for a plume contained within a mixing layer. That is, terrain intersection is permitted for all stability categories, but only for a plume contained within the surface mixing layer.

A.6 PROCEDURES USED TO CALCULATE OCCURRENCE FREQUENCIES OF HOURLY CONCENTRATIONS

This section describes procedures to calculate the annual probability of measuring hourly ground-level concentrations, produced by emissions from a single stack, that are greater than or equal to a selected threshold concentration χ_{TH}. Meteorological inputs required for the calculations include the annual distribution of wind-speed and wind-direction categories classified according to stability or time-of-day categories. By knowing the fraction of the time that the threshold concentration is exceeded, the calculated probabilities can be converted to convenient units such as hours per year. Occurrence frequencies calculated using these procedures will be essentially the same as those calculated using a year of sequential hourly meteorological data.

Whenever the maximum ground-level concentration χ_{max} exceeds the threshold concentration χ_{TH}, an approximately elliptical area will exist within which the ground-level concentration is greater than or equal to χ_{TH}. This concept is illustrated in Figure A-3. The x axis in the figure is the downwind axis, the y axis is the crosswind axis and the vertical axis is the concentration axis. The ratio γ of the threshold concentration χ_{TH} to the maximum ground-level concentration χ_{max} determines the size of this ellipse.

The maximum ground-level concentration may be easily calculated by making the following simplifications in the short-term concentration model described in Section A.3:

- The mixing depth H_m is assumed to be much greater than the plume stabilization height H (i.e., $H_m >> H$)

- Equation (A-11) is replaced by the simplified expression

$$\sigma_y = \sigma'_A x^{\alpha} \qquad \text{(A-38)}$$

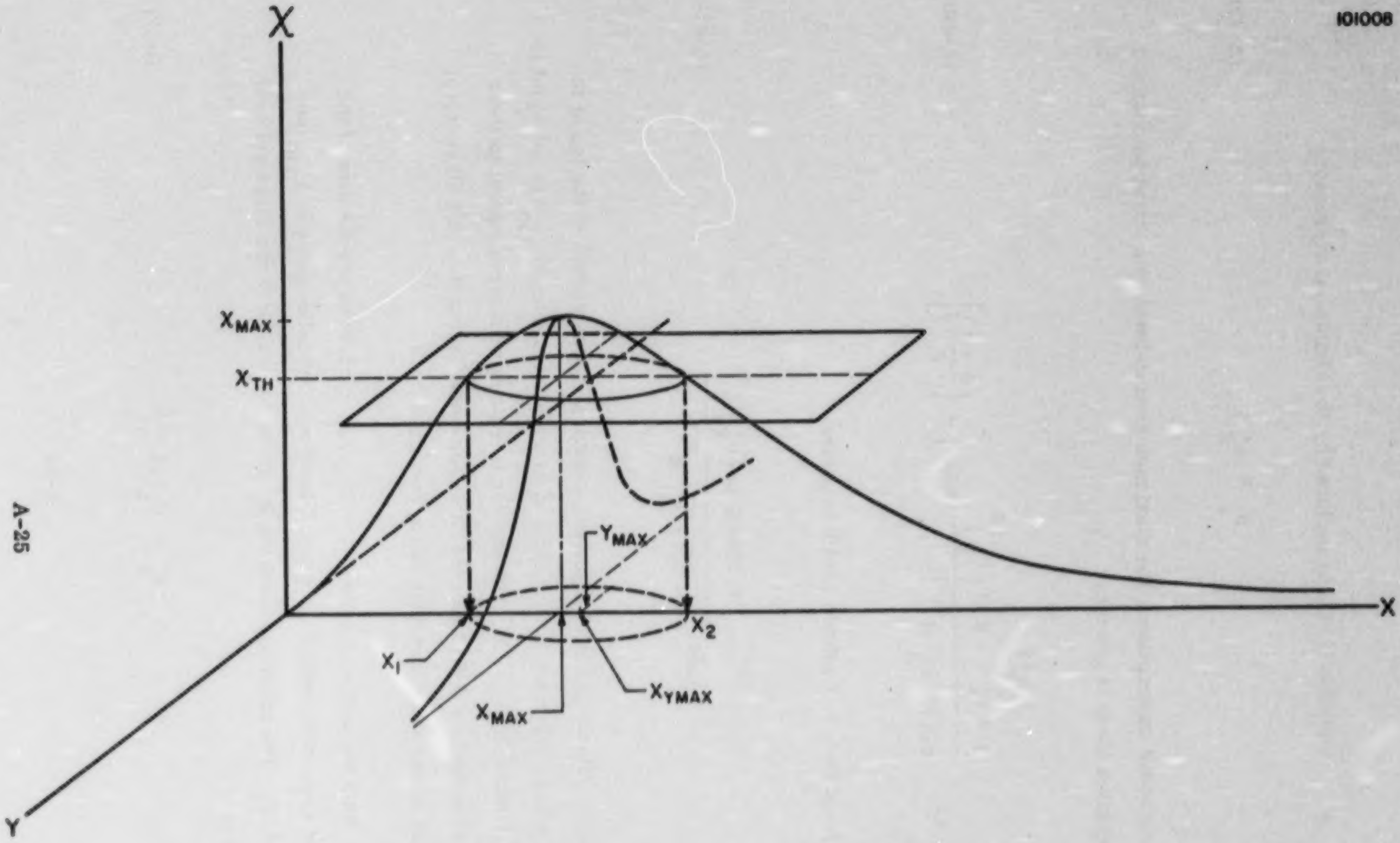

FIGURE A-3. Illustration of the approximately elliptical area within which the ground-level concentration is greater than or equal to the threshold concentration χ_{TH}.

- Equation (A-13) is replaced by the simplified expression

$$\sigma_z = \sigma'_E\, x \tag{A-39}$$

Under the above assumptions, the maximum ground-level concentration obtained from Equation (A-5) is given by

$$\chi_{max} = \frac{(\alpha + 1)^{\frac{\alpha+1}{2}} \; K\, Q \left(\sigma'_E\right)^{\alpha}}{\pi\, \bar{u}\{H\}\; \sigma'_A \; H^{(\alpha+1)}} \exp\left[-\left(\frac{\alpha+1}{2}\right)\right] \tag{A-40}$$

For α equal to 0.9, Equation (A-40) becomes

$$\chi_{max} = \frac{0.2265\; K\, Q \left(\sigma'_E\right)^{0.9}}{\bar{u}\{H\}\; \sigma'_A \; H^{1.9}} \tag{A-41}$$

Although the effects of the restriction on vertical plume growth at the top of the surface mixing layer are not considered in the calculations, χ_{max} is set equal to zero if H exceeds H_m. Adjustments for terrain effects are identical to those described in Section A.5 except that it is necessary to assume that all receptor points are at the same elevation above mean sea level.

As noted above, the ratio $\gamma = \chi_{TH}/\chi_{max}$ determines the size of the elliptical area within which the ground-level concentration exceeds χ_{TH} (see Figure A-3). The minimum distance x_1 from the source to the elliptical area is given by

$$x_1 = C_1\{\gamma\} \frac{H}{\sigma'_E} \tag{A-42}$$

The maximum distance x_2 at which concentrations greater than or equal to χ_{TH} can occur is given by

$$x_2 = C_2\{\gamma\} \frac{H}{\sigma'_E} \tag{A-43}$$

The distance x_{ymax} from the source to the center of the ellipse is then given by

$$x_{ymax} = \frac{(x_1 + x_2)}{2} \tag{A-44}$$

Finally, the semi-minor axis y_{max} of the ellipse is given by

$$y_{max} = C_3\{\gamma\} \sigma'_A \left(\frac{H}{\sigma'_E}\right)^{0.9} \tag{A-45}$$

The coefficients $C_1\{\gamma\}$, $C_2\{\gamma\}$ and $C_3\{\gamma\}$ are listed in Table A-3. It should be noted that these coefficients and Equations (A-42) through (A-45) assume that the lateral diffusion coefficient α is equal to 0.9.

Equations (A-41) through (A-45), which allow one to readily determine the area within which the threshold concentration is equalled or exceeded, form the basis for the following probability calculation procedures:

(1) For each wind-speed/stability combination, calculate $\chi_{max;i,k}$.

(2) For each wind-speed/stability combination, calculate $\gamma_{i,k} = \chi_{TH}/\chi_{max;i,k}$.

TABLE A-3

COEFFICIENTS FOR CALCULATING THE DIMENSIONS OF ELLIPSES WITHIN WHICH THE CONCENTRATION IS GREATER THAN OR EQUAL TO χ_{TH}

γ	$C_1\{\gamma\}$	$C_2\{\gamma\}$	$C_3\{\gamma\}$
0.10	0.323106	3.951545	2.941260
0.20	0.357991	2.690688	2.003900
0.30	0.386236	2.126670	1.551049
0.40	0.412444	1.783548	1.255806
0.50	0.438581	1.542262	1.033335
0.60	0.466111	1.356514	0.849163
0.70	0.496744	1.203265	0.684611
0.80	0.533358	1.068030	0.525411
0.90	0.583162	0.936680	0.351782
0.95	0.620825	0.863202	0.242594
0.99	0.675747	0.781617	0.106428
1.00	0.725476	0.725476	0.000000

(3) All wind-speed/stability combinations for which $\gamma_{i,k} \geq 1$ need not be considered; assign zero frequencies to these combinations and normalize the frequencies of occurrence of the remaining wind-speed/stability combinations within each wind-direction sector by dividing by the total frequency of occurrence for all wind-direction sectors of the wind-speed/stability combinations for which $\gamma_{i,k} < 1$. These adjusted frequency distributions will be used to determine the probability of observing concentrations above the threshold χ_{TH} at each grid point (r, θ).

(4) For each of the remaining wind-speed/stability combinations, calculate $x_{1;i,k}$, $x_{2;i,k}$, $x_{ymax;i,k}$ and $y_{max;i,k}$.

(5) For each grid point (r, θ), calculate the probability $f'\{r, \theta\}_{i,k}$ of observing a concentration above the short-term threshold concentration χ_{TH} as a result of the i^{th} wind-speed category and k^{th} stability category, where

$$f'_{i,k}\{r, \theta\} = \sum_{j} P_{i,j,k}\{r, \theta\}\, f'_{i,j,k} \qquad \text{(A-46)}$$

and $f'_{i,j,k}$ is the adjusted (normalized) frequency of occurrence of the i^{th} wind-speed category, j^{th} wind-direction category and k^{th} stability category. The equations defining $P_{i,j,k}$ are given below.

(6) For each grid point (r, θ), calculate the total probability $F\{r, \theta\}$ of observing concentrations greater than or equal to χ_{TH} from the equation

$$F\{r,\theta\} = \sum_{i,k} f_{i,k}\{r,\theta\} \qquad \text{(A-47)}$$

The weighting factor $P_{i,j,k}\{r,\theta\}$ is determined by the ratio of the angular width of the portion of the elliptical area contained within the wind-direction sector at downwind distance r to the angular width $\Delta\theta'$ of the sector. That is, $P_{i,j,k}$ is given by

$$P_{i,j,k}\{r,\theta\} = \left\{ \begin{array}{ll} 0 & ;\ B \geq \Delta\theta' \\ 0 & ;\ \dfrac{\left(\delta_{i,k}\{r\} + \Delta\theta'\right)}{2} \leq B < \Delta\theta' \\ \left[\dfrac{\left(\delta_{i,k}\{r\} + \Delta\theta'\right)/2 - B}{\Delta\theta'}\right] & ;\ \dfrac{\left(\Delta\theta' - \delta_{i,k}\{r\}\right)}{2} \leq B < \dfrac{\left(\Delta\theta' + \delta_{i,k}\{r\}\right)}{2} \\ \dfrac{\delta_{i,k}\{r\}}{\Delta\theta'} & ;\ B < \dfrac{\left(\Delta\theta' - \delta_{i,k}\{r\}\right)}{2} \end{array} \right\} \qquad \text{(A-48)}$$

$$B = \left\{ \begin{array}{ll} \left|\theta' - \theta'_j\right| & ;\ \left|\theta' - \theta'_j\right| \leq \pi \\ 2\pi - \left|\theta' - \theta'_j\right| & ;\ \left|\theta' - \theta'_j\right| > \pi \end{array} \right\} \qquad \text{(A-49)}$$

$$\delta_{i,k}\{r\} = 2 \arctan\left[\frac{y\{r\}_{i,k}}{r}\right] \qquad \text{(A-50)}$$

$$
y\{r\}_{i,k} = \left\{ \begin{array}{ll} y_{\max;i,k}\left[1 - \frac{4\left(r - x_{y\max;i,k}\right)^2}{\left(x_{2;i,k} - x_{1;i,k}\right)^2}\right]^{1/2} & ; x_{1;i,k} \le r \le x_{2;i,k} \\ 0 & ; r < x_{1;i,k} \quad \text{or} \\ & r > x_{2;i,k} \end{array} \right\} \qquad \text{(A-51)}
$$

It should be noted that $P_{i,j,k}$ is not permitted to exceed unity and $\delta_{i,k}$ is assumed to be less than $\Delta\theta'$.

If T is the fraction of the time during the year that χ_{max} is greater than or equal to χ_{TH}, the number of hours per year that the hourly concentration at the point (r, θ) is greater than or equal to χ_{TH} can be estimated from the expression

$$
\begin{aligned} \{\text{Hours/year}\} &= F\{r,\theta\}\,(T)\,(365)\,(24) \\ &= 8760\, F\{r,\theta\}\, T \end{aligned} \qquad \text{(A-52)}
$$

APPENDIX B

ANNUAL FREQUENCY DISTRIBUTION OF WIND SPEED AND WIND DIRECTION AT N26th AND PEARL

Tables B-1 through B-6 list the annual joint frequency of occurrence by Pasquill stability category of wind-speed and wind-direction categories at N26th and Pearl for the year 1972. These distributions were developed from concurrent hourly cloud cover observations at McChord Air Force Base and hourly wind measurements at the Puget Sound Air Pollution Control Agency's meteorological tower at N26th and Pearl by the STAR program of the National Climatic Center. This computer program uses the Turner (1964) definitions of the Pasquill stability categories (see Section 3.1). As explained in Section 3.3, we combined the E and F stability categories in our calculations because we believe that surface roughness elements and heat sources in the Tacoma are incompatible with the minimal turbulent mixing associated with the Pasquill F stability category. Also, the A and B stability categories were combined in the annual concentration calculations because the A stability category only occurs about 0.4 percent of the time in the Tacoma area (see Table B-1).

TABLE B-1

1972 ANNUAL FREQUENCY DISTRIBUTION OF WIND SPEED AND WIND DIRECTION AT N26th AND PEARL FOR THE A STABILITY CATEGORY

Direction (Sector)	Wind Speed (meters per second)						
	00.0-01.5	01.6-03.0	03.1-05.1	05.2-08.2	08.3-10.8	> 10.8	Total
N	.0000	.0000	.0000	.0000	.0000	.0000	.0000
NNE	.0000	.0493	.0000	.0000	.0000	.0000	.0493
NE	.0616	.0246	.0000	.0000	.0000	.0000	.0862
ENE	.0369	.0000	.0000	.0000	.0000	.0000	.0369
E	.0000	.0000	.0000	.0000	.0000	.0000	.0000
ESE	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SE	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SSE	.0000	.0000	.0000	.0000	.0000	.0000	.0000
S	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SSW	.0123	.0000	.0000	.0000	.0000	.0000	.0123
SW	.0000	.0246	.0000	.0000	.0000	.0000	.0246
WSW	.0123	.0246	.0000	.0000	.0000	.0000	.0369
W	.0369	.0256	.0000	.0000	.0000	.0000	.0616
WNW	.0246	.0123	.0000	.0000	.0000	.0000	.0369
NW	.0246	.0000	.0000	.0000	.0000	.0000	.0246
NNW	.0493	.0000	.0000	.0000	.0000	.0000	.0493
Total	.2586	.1601	.0000	.0000	.0000	.0000	.4187

TABLE B-2

1972 ANNUAL FREQUENCY DISTRIBUTION OF WIND SPEED AND WIND DIRECTION AT N26th AND PEARL FOR THE B STABILITY CATEGORY

Direction (Sector)	Wind Speed (meters per second)						
	00.0-01.5	01.6-03.0	03.1-05.1	05.2-08.2	08.3-10.8	> 10.8	Total
N	.1486	.1724	.1601	.0000	.0000	.0000	.4812
NNE	.4197	.5049	.3325	.0000	.0000	.0000	1.2572
NE	.5219	.4926	.2956	.0000	.0000	.0000	1.3101
ENE	.2364	.1232	.0000	.0000	.0000	.0000	.3596
E	.0642	.0000	.0000	.0000	.0000	.0000	.0642
ESE	.0128	.0000	.0000	.0000	.0000	.0000	.0128
SE	.0000	.0000	.0000	.0000	.0000	.0000	.0000
SSE	.0391	.0123	.0000	.0000	.0000	.0000	.0514
S	.0519	.0123	.0000	.0000	.0000	.0000	.0642
SSW	.1027	.0000	.0000	.0000	.0000	.0000	.1027
SW	.1455	.0985	.1601	.0000	.0000	.0000	.4041
WSW	.3657	.4433	.2094	.0000	.0000	.0000	1.0184
W	.5130	.2833	.0493	.0000	.0000	.0000	.8455
WNW	.2846	.0493	.0000	.0000	.0000	.0000	.3339
NW	.3221	.0246	.0000	.0000	.0000	.0000	.3467
NNW	.2322	.0246	.0000	.0000	.0000	.0000	.2568
Total	3.4606	2.2414	1.2069	.0000	.0000	.0000	6.9089

TABLE B-3

1972 ANNUAL FREQUENCY DISTRIBUTION OF WIND SPEED AND WIND DIRECTION AT N26th AND PEARL FOR THE C STABILITY CATEGORY

Direction (Sector)	Wind Speed (meters per second)						
	00.0-01.5	01.6-03.0	03.1-05.1	05.2-08.2	08.3-10.8	> 10.8	Total
N	.3229	.1970	.3695	.0616	.0000	.0000	.9510
NNE	.2518	.4187	1.3054	.3202	.0000	.0000	2.2961
NE	.4598	.6897	.7882	.0739	.0000	.0000	2.0115
ENE	.1970	.1724	.0246	.0000	.0000	.0000	.3941
E	.0972	.0123	.0123	.0000	.0000	.0000	.1218
ESE	.0424	.0123	.0000	.0000	.0000	.0000	.0547
SE	.0547	.0000	.0000	.0000	.0000	.0000	.0547
SSE	.1136	.0369	.0123	.0000	.0000	.0000	.1628
S	.1204	.0985	.0369	.0000	.0000	.0000	.2559
SSW	.1204	.0985	.1108	.0123	.0000	.0000	.3421
SW	.2969	.3325	.4433	.0369	.0000	.0000	1.1097
WSW	.2723	.4803	.4064	.0123	.0000	.0000	1.1713
W	.2354	.1478	.0493	.0000	.0000	.0000	.4324
WNW	.1574	.0616	.0123	.0000	.0000	.0000	.2313
NW	.1136	.0369	.0000	.0000	.0000	.0000	.1505
NNW	.1245	.0123	.0123	.0000	.0000	.0000	.1492
Total	2.9803	2.8079	3.5837	.5172	.0000	.0000	9.8892

TABLE B-4

1972 ANNUAL FREQUENCY DISTRIBUTION OF WIND SPEED AND WIND DIRECTION AT N26th AND PEARL FOR THE D STABILITY CATEGORY

Direction (Sector)	Wind Speed (meters per second)						
	00.0-01.5	01.6-03.0	03.1-05.1	05.2-08.2	08.3-10.8	> 10.8	Total
N	.7113	.5172	.1970	.1108	.0000	.0000	1.5364
NNE	.9294	1.3300	1.3670	1.3916	.1601	.0123	5.1904
NE	1.1694	1.3300	1.2192	1.0345	.0369	.0000	4.7901
ENE	.6241	.3079	.1601	.1355	.0739	.0000	1.3015
E	.3558	.3079	.0739	.0739	.0000	.0000	.8115
ESE	.5550	.2217	.1478	.0123	.0000	.0000	.9368
SE	.4507	.1847	.0862	.0246	.0000	.0000	.7463
SSE	1.1473	.5049	.2340	.0739	.0000	.0000	1.9601
S	1.6430	1.4778	.8251	.5049	.0862	.0000	4.5371
SSW	1.3568	1.9335	3.2759	2.9557	.3941	.0493	9.9651
SW	1.3308	2.6232	3.9286	3.2882	.3818	.0493	11.6018
WSW	1.2177	2.0443	1.6995	1.4409	.4064	.0985	6.9074
W	1.1254	.8374	.2094	.0616	.0000	.0000	2.2338
WNW	.5000	.1355	.0000	.0000	.0000	.0000	.6355
NW	.3215	.0739	.0000	.0000	.0000	.0000	.3954
NNW	.2933	.0739	.0123	.0123	.0000	.0000	.3918
Total	13.7315	13.9039	13.4360	11.1207	1.5394	.2094	53.9409

TABLE B-5

1972 ANNUAL FREQUENCY DISTRIBUTION OF WIND SPEED AND WIND DIRECTION AT N26th AND PEARL FOR THE E STABILITY CATEGORY

Direction (Sector)	Wind Speed (meters per second)						
	00.0-01.5	01.6-03.0	03.1-05.1	05.2-08.2	08.3-10.8	> 10.8	Total
N	.0000	.1108	.0493	.0000	.0000	.0000	.1601
NNE	.0000	.7882	.7759	.0000	.0000	.0000	1.5640
NE	.0000	.6897	.8744	.0000	.0000	.0000	1.5640
ENE	.0000	.1232	.0862	.0000	.0000	.0000	.2094
E	.0000	.1232	.0369	.0000	.0000	.0000	.1601
ESE	.0000	.0739	.0369	.0000	.0000	.0000	.1108
SE	.0000	.1232	.0123	.0000	.0000	.0000	.1355
SSE	.0000	.3079	.0985	.0000	.0000	.0000	.4064
S	.0000	.8744	.1232	.0000	.0000	.0000	.9975
SSW	.0000	.7266	.2463	.0000	.0000	.0000	.9729
SW	.0000	.7143	.1970	.0000	.0000	.0000	.9113
WSW	.0000	.3571	.2586	.0000	.0000	.0000	.6158
W	.0000	.0369	.0246	.0000	.0000	.0000	.0616
WNW	.0000	.0369	.0000	.0000	.0000	.0000	.0369
NW	.0000	.0123	.0000	.0000	.0000	.0000	.0123
NNW	.0000	.0123	.0000	.0000	.0000	.0000	.0123
Total	.0000	5.1108	2.8202	.0000	.0000	.0000	7.9310

TABLE B-6

1972 ANNUAL FREQUENCY DISTRIBUTION OF WIND SPEED AND WIND DIRECTION AT N26th AND PEARL FOR THE F STABILITY CATEGORY

Direction (Sector)	Wind Speed (meters per second)						
	00.0-01.5	01.6-03.0	03.1-05.1	05.2-08.2	08.3-10.8	> 10.8	Total
N	1.1341	.3202	.0000	.0000	.0000	.0000	1.4543
NNE	1.5243	1.1700	.0000	.0000	.0000	.0000	2.6943
NE	1.8145	1.2931	.0000	.0000	.0000	.0000	3.1076
ENE	.8769	.3325	.0000	.0000	.0000	.0000	1.2094
E	.4616	.1355	.0000	.0000	.0000	.0000	.5970
ESE	.4469	.0123	.0000	.0000	.0000	.0000	.4593
SE	.4622	.0123	.0000	.0000	.0000	.0000	.4746
SSE	1.4925	.2833	.0000	.0000	.0000	.0000	1.7758
S	1.2592	.3941	.0000	.0000	.0000	.0000	1.6533
SSW	1.2529	.4310	.0000	.0000	.0000	.0000	1.6839
SW	1.3990	.5911	.0000	.0000	.0000	.0000	1.9901
WSW	.7687	.5172	.0000	.0000	.0000	.0000	1.2859
W	.6606	.1355	.0000	.0000	.0000	.0000	.7960
WNW	.5511	.0000	.0000	.0000	.0000	.0000	.5511
NW	.5112	.0246	.0000	.0000	.0000	.0000	.5358
NNW	.5814	.0616	.0000	.0000	.0000	.0000	.6430
Total	15.1970	5.7143	.0000	.0000	.0000	.0000	20.9113

APPENDIX C

EMISSIONS DATA FOR THE OTHER MAJOR SO_2 SOURCES IN THE SEATTLE-TACOMA AREA

Table C-1 lists the locations and the stack and emissions data for the major SO_2 sources in the Seattle-Tacoma area other than the ASARCO smelter. The parameters in Table C-1, which were developed from information provided by PSAPCA, were used in all diffusion-model calculations described in this report unless otherwise noted.

In two cases (Tacoma City Light and Seattle City Light), a source complex consisted of two or more stacks in close proximity and with identical stack and emissions parameters. In order to reduce computer computational time without loss of accuracy, the SO_2 emissions for these stacks were combined and assumed to originate from a single stack with a volumetric emission rate and exit temperature equal to the volumetric emission rate and exit temperature of the individual stacks. For these two cases, Table C-1 also lists the number of stacks.

For the reasons discussed in Appendix D, exit-velocity restrictions on plume rise were not included in the diffusion-model calculations for stacks with Froude numbers less than 3.0. The stack radius for a stack with Froude number less than 3.0 is shown as zero in Table C-1.

TABLE C-1

LOCATIONS AND STACK AND EMISSIONS DATA FOR THE MAJOR SO_2 SOURCES IN THE SEATTLE-TACOMA AREA

Source Name	Source Number	SO_2 Emissions (tons/yr)	UTM X Coordinate (m)	UTM Y Coordinate (m)	Elevation of Stack Base (m above MSL)	Stack Height (m)	Stack Radius (m)	Volumetric Emission Rate (m^3/sec)	Stack Exit Temp. (^oK)
Dupont de Nemours & Co.	1	101.0	525800	5217250	70	46	-0-	2.74	436
Hooker Chemicals & Plastics	2	196.0	545240	5236190	2	58	-0-	16.33	426
Pennwalt	3	36.6	547240	5234890	2	18	.65	9.34	436
	4	36.6	547240	5234890	2	46	-0-	9.34	533
St. Regis Kraft Mill	5	95.0	543300	5234800	2	53	-0-	42.03	405
	6	150.0	543300	5234800	2	46	.84	70.05	405
	7	97.0	543300	5234800	2	88	1.33	56.04	335
	8	237.0	543300	5234800	2	84	2.13	151.78	451
	9	4.0	543300	5234800	2	23	1.07	38.29	480
	10	6.0	543300	5234800	2	53	1.30	58.38	491
	11	964.0	543300	5234800	2	30	.99	24.28	422
	12	375.0	543300	5234800	2	25	.68	17.00	422

TABLE C-1

LOCATIONS AND STACK AND EMISSIONS DATA FOR THE MAJOR SO_2 SOURCES IN THE SEATTLE-TACOMA AREA

Source Name	Source Number	SO_2 Emissions (tons/yr)	UTM X Coordinate (m)	UTM Y Coordinate (m)	Elevation of Stack Base (m above MSL)	Stack Height (m)	Stack Radius (m)	Volumetric Emission Rate (m^3/sec)	Stack Exit Temp. (°K)
Quemetco	13	1,410.4	548800	5269500	3	27	.46	9.33	366
U.S. Oil & Refining	14	310.0	545800	5233610	4	33	-0-	22.38	626
U.S. Gypsum	15	52.7	547730	5234600	6	7	.23	4.25	394
Boise Cascade	16	34.8	532250	5225500	58	61	-0-	26.15	505
	17	8.8	532250	5225500	58	17	.61	9.34	519
Boeing-Renton	19	33.7	558600	5261500	9	12	.43	8.50	422
Kaiser-Aluminum	20	1,931.3	547600	5234000	4	9	---	30.0*	30*
Western Seattle Steam	21	152.0	549900	5272500	20	40	.97	56.63	450
Shell Oil	22	94.0	549140	5269800	3	30	-0-	3.50	422
	23	70.0	549140	5269800	3	9	-0-	1.40	422
Texaco	24	26.1	548900	5269700	3	21	-0-	.42	467
U.S.N.-Sand Point	25	31.4	555500	5281400	15	11	-0-	8.64	505

* Indicates building source; building length and width are entered as stack exit temperature and volumetric emission rate.

TABLE C-1

LOCATIONS AND STACK AND EMISSIONS DATA FOR THE MAJOR SO_2 SOURCES IN THE SEATTLE-TACOMA AREA

Source Name	Source Number	SO_2 Emissions (tons/yr)	UTM X Coordinate (m)	UTM Y Coordinate (m)	Elevation of Stack Base (m above MSL)	Stack Height (m)	Stack Radius (m)	Volumetric Emission Rate (m^3/sec)	Stack Exit Temp. (^oK)
Veterans Hospital - Tacoma	26	73.2	532300	5220000	75	38	-0-	4.67	422
McChord AFB	27	159.0	539150	5220020	84	6	-0-	23.33	491
Pier 91	29	143.0	546400	5275500	2	9	-0-	18.36	505
McNeil Penitentiary	30	97.9	525500	5227500	55	46	-0-	2.26	422
Milwaukee RR Switchyard	31	29.5	544500	5234500	2	10	-0-	1.20	450
Tacoma City Light Plant 2	32	566.0 (2 stacks)	546900	5235900	6	42	-0-	35.87	505
Seattle City Light Lake Union Plant	34	410.9 (7 stacks)	550900	5276400	43	51	-0-	6.61	477
Seattle Public Safety Bldg.	41	50.4	550300	5272300	31	55	-0-	2.36	366
Seattle Center	42	40.6	548900	5274200	35	27	.51	9.80	477

TABLE C-1

LOCATIONS AND STACK AND EMISSIONS DATA FOR THE MAJOR SO_2 SOURCES IN THE SEATTLE-TACOMA AREA

Source Name	Source Number	SO_2 Emissions (tons/yr)	UTM X Coordinate (m)	UTM Y Coordinate (m)	Elevation of Stack Base (m above MSL)	Stack Height (m)	Stack Radius (m)	Volumetric Emission Rate (m^3/sec)	Stack Exit Temp. (°K)
University of Washington	43	96.7	552000	5277500	27	61	1.68	139.38	394
Veterans Hospital-Seattle	44	37.6	552000	5267800	98	37	-0-	2.83	422
Seattle-Tacoma Airport	45	129.2	553010	5253890	117	15	.30	2.36	450
Standard Oil	46	52.0	549600	5270200	9	10	-0-	.94	533

APPENDIX D

EXIT-VELOCITY RESTRICTIONS ON PLUME RISE AND THE ASARCO PLUME

In most plume rise equations, including those of Briggs (1969, 1970, 1971 and 1972), momentum effects are neglected when calculating buoyant plume rise. There are sound theoretical and empirical reasons to believe that momentum effects are negligible in comparison with buoyancy effects for a hot stack. However, Briggs (1969), Fay, et al., (1970) and others have expressed the belief that their plume rise equations may not be applicable when the ratio of the stack exit velocity w to the mean wind speed $\bar{u}$ is less than 1.5 to 1.2 unless the Froude number Fr is less than about unity. The Froude number Fr, which in essence is the ratio of momentum to buoyancy, is defined by Briggs (1969, p. 6) as

$$Fr = \frac{w^2}{g\left(\frac{T_s - T_a}{T_a}\right)D} \qquad \text{(D-1)}$$

where

T_s = the stack exit temperature ($^{\circ}$K)

T_a = the ambient air temperature ($^{\circ}$K)

D = the stack diameter (m)

g = the acceleration due to gravity (m/sec^2)

Thus, a stack with a small Froude number will have a high heat content. For $w/\bar{u}$ less than 1.2, Briggs (1970) states that "downwash of the plume into the low pressure region in the wake of the stack is likely to occur." The ASME Guide (1973, p. 23-25) recommends that a stack should be designed so that $w/\bar{u}$ is greater than or equal to 2 most of the time. As shown in Table D-1, most of the stacks used to validate the Briggs plume rise equations have either high exit velocities or

TABLE D-1

EXIT VELOCITIES AND FROUDE NUMBERS OF STACKS USED TO VALIDATE THE BRIGGS (1969) PLUME RISE EQUATIONS

Source*	Exit Velocities (m/sec)	Froude Number
Harwell A**	9.9	17.6
Harwell B	9.9	17.6
Bosanquett**	9.7	3.0
Darmstadt**	4.8	0.9
Duisburg	8.5	5.6
Tallawarra**	3.7	0.5
Lakeview**	19.8	19.9
CEGB Plants		
Earley	5.6	1.9
Earley	17.1	17.7
Castle Donington	12.5	5.3
Castle Donington	16.7	9.5
Northfleet**	14.1	10.9
Northfleet**	21.3	24.9
TVA Plants		
Shawnee**	14.8	11.9
Colbert**	13.1	7.7
Johnsonville	28.9	43.8
Widows Creek	21.8	18.5
Gallatin	16.0	8.9
Gallatin	7.2	1.5
Paradise	15.6	20.6
Paradise	17.4	8.9

* See Table 5.1 of Briggs (1969) for data references.

**Not included in "selected data" by Briggs (1969) because factors such as low exit velocity, terrain downwash, etc. may affect plume rise.

low Froude numbers. Thus, any exit velocity effects on plume rise would not be observed for these stacks except on rare occasion.

During 1974 and 1975, the H. E. Cramer Company developed a computerized set of short-term and long-term urban diffusion models and used them to calculate ground-level concentrations produced by the major stationary SO_2 sources in Lansing, Michigan and Allegheny County, Pennsylvania. During the two studies, we found that visual observations of the behavior of the plumes from a number of stacks did not correspond to the behavior predicted by the Briggs equations when the wind speed approached the stack exit velocities. Observations suggested that, rather than attaining the calculated plume rise, the plumes did not achieve any buoyant rise when the wind speed was greater than or equal to the stack exit velocities. In general, these stacks were characterized by Froude numbers appreciably larger than unity.

On the basis of our observations in Lansing and Allegheny County, we hypothesized that plume rise is precluded for most stacks when $w/\bar{u}$ is less than or equal to unity. Following the suggestions of Briggs (1973), we assumed that the exit-velocity effect starts to occur when $w/\bar{u}$ is equal to 1.5. We therefore multiplied the plume rise Δh calculated from the Briggs equations by a factor f defined by

$$f = \left\{ \begin{array}{ll} 1 & ; \; \bar{u} < w/1.5 \\ \dfrac{3w_s - 3\bar{u}}{w_s} & ; \; w/1.5 \le \bar{u} < w \\ 0 & ; \; w \le \bar{u} \end{array} \right\} \qquad \text{(D-2)}$$

The expression in Equation (D-2) for $\bar{u}$ between 0.67 w and w is a simple linear interpolation between the two extremes that we hypothesized. Equation (D-2) corresponds to Equation (A-3) in Appendix A.

The use of Equation (D-2) in long-term and short-term diffusion model calculations substantially improved the correspondence between the calculated and observed concentrations in every case. One 24-hour historical case in Allegheny County was of particular interest. For this case, we had reported visual observations that the plumes from a power plant passed directly over an air quality monitor for much of the day. The plumes behaved in the manner predicted by our modified plume rise formulas, and the ratios of calculated and observed maximum 3-hour and 24-hour average concentrations were 1.17 and 1.10, respectively. This case is discussed in a recent report prepared for EPA (Cramer, et al., 1975).

Since completion of the Allegheny County and Lansing studies, we have continued our study of exit-velocity restrictions on plume rise. We have obtained aircraft measurements made by the EPA Environmental Monitoring and Support Laboratory (EMSL) of plume rise for three coal-fired power plants during periods when the wind speed at stack height was equal to or greater than the stack exit velocity. Also, we have analyzed the plume-rise data of Bringfelt (1968), although Bringfelt and Briggs (1970) point out that there are some deficiencies in these data. We have found that, for stacks with Froude numbers greater than 3.0, the Briggs plume rise equations significantly overestimate plume rise as the wind speed approaches or exceeds the stack exit velocity. If our semi-empirical correction factor f is applied to the Bringfelt trials with the potential for exit-velocity effects ($w/\bar{u} \leq 1.5$ and $Fr \geq 3.0$), the correspondence between calculated and observed plume rise is essentially the same as obtained for the trials without exit-velocity effects. We have found no evidence in the Bringfelt data or the EMSL observations of exit-velocity restrictions on plume rise for stacks with Froude number less than 1.0. For stacks with Froude numbers between 1.0 and 3.0, some stacks appear to exhibit exit-velocity effects and some do not. Because the Froude number of the ASARCO stack varies from 1.5 to 2.8 (depending on the number of stack heaters), there is some uncertainty about the behavior of the

ASARCO plume as the wind speed at stack height approaches the stack exit-velocity (about 6 meters per second).

During our background study of the ASARCO smelter, we hypothesized that, if exit-velocity restrictions on plume rise applied to the ASARCO stack, high short-term ground-level concentrations would begin about 1 kilometer southwest of the stack during periods of moderate-to-strong northeast winds. To test our hypothesis, EPA Region X located a continuous SO_2 monitor at a distance of about 1.2 kilometers and at an azimuth bearing of 215 degrees from the stack. Table D-2 lists the hourly ground-level SO_2 concentrations greater than or equal to the PSAPCA hourly standard of 0.25 ppm measured during the period 18 September 1975 through 27 January 1976. For days with several consecutive hours with concentrations above 0.25 ppm, the time and magnitude of the maximum hourly concentration are shown in parentheses in the table.

Not all of the high SO_2 concentrations listed in Table D-2 occurred during periods of moderate-to strong northeast winds, the conditions that we hypothesized as leading to the highest short-term concentrations. Some of the high concentrations occurred with light northeast winds or during air stagnation. The most clearly defined cases of observed high hourly concentrations at the EPA monitor occurred on the night of 18-19 September 1975. The hourly ground-level concentrations calculated from meteorological data and ASARCO in-stack SO_2 concentration measurements provided by PSAPCA, assuming exit-velocity restrictions on plume rise, ranged from 2.5 to 10 times lower than the observed concentrations. The calculated concentrations that were about 10 times lower than the observed concentrations could be substantially increased by a slight increase in the wind speed or a slight decrease in the stack exit-velocity (the correction factor f is extremely sensitive to the ratio $w/\bar{u}$ for $w/\bar{u}$ between 1.5 and 1). For the hour ending at

TABLE D-2

MAXIMUM HOURLY GROUND-LEVEL SO_2 CONCENTRATIONS MEASURED BY THE EPA SO_2 MONITOR IN TACOMA

Date	Time (PST)	Concentration (ppm)
18 September 1975	2100 - 2200	0.43
	2200 - 2300	0.59
	(2136 - 2236)	(0.79)
19 September 1975	0200 - 0300	0.30
24 September 1975	1048 - 1148	0.27
30 September 1975	1324 - 1424	0.29
	1700 - 1800	0.71
	1800 - 1900	0.31
	(1712 - 1812)	0.75
1 October 1975	1724 - 1824	0.44
24 November 1975	1448 - 1548	0.28
19 December 1975	1100 - 1200	0.35
	1200 - 1300	0.45
	1300 - 1400	0.27
	(1206 - 1306)	0.47
20 January 1976	0900 - 1000	0.43

2300 PST on 18 September, the wind speed at stack height exceeded the exit velocity (i.e., the calculated plume rise was zero) and the calculated concentration was 2.5 times lower than the observed concentration. The ASARCO in-stack SO_2 concentration data indicated a very low emission rate for this hour. If the maximum uncurtailed emission rate is used, the calculated concentration exceeds the observed concentration (the curtailment report does not indicate any curtailment in smelter operations during this hour). We repeated the concentration calculations without assuming exit-velocity restrictions and, in every case, the calculated concentration at the EPA monitor was zero.

For the majority of the cases listed in Table D-2, we believe that the observed wind directions clearly establish that the smelter was the source of the SO_2 measured by the EPA monitor. Assuming that the ASARCO in-stack SO_2 concentration data are valid on a short-term basis, the majority of the measured SO_2 concentrations at the EPA monitor could not have been caused by emissions from the main stack. It is therefore necessary to hypothesize continuous low-level SO_2 emissions on the order of 1,000 pounds per hour to account for the observed concentrations. Low-level fugitive emissions occur during certain phases of production (Weisenberg and Serne, 1976), but there is no record of either their magnitude or time duration.

In summary, we were not able to establish whether exit-velocity restrictions on plume rise apply to the main ASARCO stack because of uncertainties in the SO_2 emissions from the main stack and from low-level fugitive sources. The PSAPCA and ASARCO SO_2 monitors in the area are too far from the stack to be useful in establishing whether exit-velocity effects are occurring. Because there remains a reasonable doubt that exit-velocity restrictions on plume rise should be applied to the ASARCO stack, we did not include exit-velocity effects in any of our calculations for the ASARCO stack. If exit-velocity effects had been included, the calculated maximum short-term ground-level SO_2 concentrations would have been increased by almost a factor of 4.

APPENDIX E

DISCUSSION OF THE SHORT-TERM HISTORICAL CASES

E.1 INTRODUCTION

As noted in Section 4.3, we analyzed meteorological and air quality data provided by PSAPCA and selected 20 dates when high hourly SO_2 concentrations were measured at one or more SO_2 monitors for one or more hours. We then used concurrent meteorological and emissions data to calculate concentrations at the monitor sites for comparison with the observed concentrations. The source and meteorological inputs, the calculation procedures and the results of the calculations are discussed in Section 4.3. This Appendix provides a detailed discussion of the individual cases.

In Figure E-1, a map of the Tacoma area, the + symbols show the locations of the ASARCO and PSAPCA SO_2 monitors. The ASARCO monitors are labeled A1 through A5; the PSAPCA monitors are labeled with the PSAPCA station number. Table E-1 gives the names of the ASARCO and PSAPCA SO_2 monitors identified in Figure E-1. It should be noted that the PSAPCA and ASARCO monitors at N26th and Pearl are located in close proximity, as are the PSAPCA Meeker and the ASARCO Meeker-Brown monitors.

Several of the Short-Term Historical Cases treat the occurrence of high SO_2 concentrations at the PSAPCA McMicken Heights and Tukwila monitors, which are located outside of the area shown in Figure E-1. The McMicken Heights monitor is 23.7 kilometers northeast of the main ASARCO stack (indicated by the star in Figure E-1) and the Tukwila monitor is 26.0 kilometers northeast of the stack.

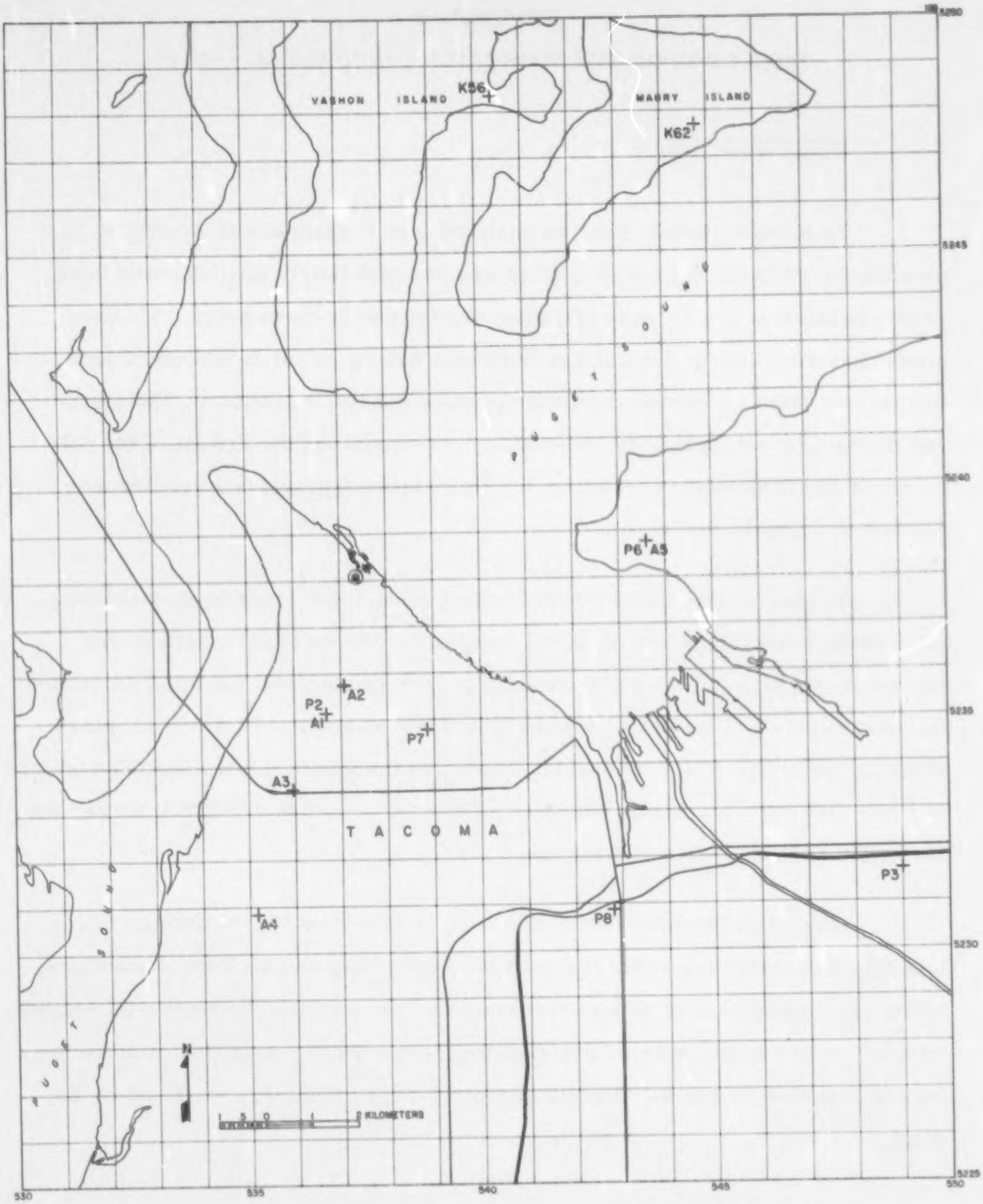

Figure E-1. Map of the Tacoma area. The + symbols show the locations of the ASARCO and PSAPCA SO_2 monitors. The star shows the location of the main ASARCO stack.

TABLE E-1

NAMES OF ASARCO AND PSAPCA SO_2 MONITORS SHOWN IN FIGURE E-1

Monitor Label in Figure E-1	Monitor Name
A1	N26th and Pearl
A2	Reservoir
A3	Highlands
A4	University Place
A5	Meeker-Brown
P2	N26th and Pearl
P3	Fife Sr. H. S.
P6	Meeker Jr. H. S.
P7	Adams Street
P8	Williard Elementary School
K56	Vashon Island
K62	Maury Island

Because the purpose of the historical calculations was to demonstrate the validity of the diffusion models and modeling procedures, we usually calculated concentrations only at the locations of the PSAPCA and ASARCO SO_2 monitors. The exceptions are Case 4 (5 July 1974) and the single 24-hour case (Case 20: 25 December 1974). Thus, we did not estimate the maximum ground-level SO_2 concentrations for most of the historical cases. However, maximum ground-level SO_2 concentrations have been calculated for the existing configuration of the ASARCO smelter (without SCS) and for possible future smelter configurations using the same modeling techniques. The results of these calculations are presented in Section 5.

E.2 DISCUSSION OF THE INDIVIDUAL CASES

E.2.1 Case 1: 29 March 1972 (Fumigation Case)

Surface winds during the early morning hours of 29 March 1972 were light and variable. With the ASARCO plume stabilizing above the top of the surface mixing layer, the ASARCO smelter operated without emissions curtailment until 0930 PST when the smelter's SCS requested 60 percent curtailment. Shortly after 1100 PST, high ground-level SO_2 concentrations began to occur in the Tacoma area. The following SO_2 concentrations in parts per million (ppm) were observed at the ASARCO and PSAPCA SO_2 monitors during the period 1100 to 1400 PST:

Hour (PST)	N26th and Pearl	Adams St.	Reservoir
1200	0.16 (0.19)	0.00	0.09
1300	0.19 (0.36)	0.36	0.38
1400	0.03 (0.08)	0.14	0.03
Average	0.13 (0.21)	0.17	0.17

where the concentrations enclosed by parentheses are the concentrations measured by the ASARCO monitor at N26th and Pearl.

The simultaneous occurrence at midday of high SO_2 concentrations N26th and Pearl, Adams Street and the Reservoir suggests a widespread fumigation. Although the ASARCO smelter's SCS requested 78 percent curtailment at 1115 PST and 88 percent curtailment at 1200 PST, it was too late to prevent hourly SO_2 concentrations above the PSAPCA hourly standard of 0.25 ppm at three separate locations for the hour ending at 1300 PST.

The calculated concentrations in ppm for the period of fumigation are:

Monitor	Calculated Concentration
N26th and Pearl	0.16
Adams St.	0.14
Reservoir	0.18

ASARCO emissions account for about 99 percent of these calculated concentrations. The concentration calculated for N26th and Pearl is approximately equal to the hourly concentrations measured by the PSAPCA monitor at N26th and Pearl for the hours ending at 1200 and 1300 PST. However, the calculated concentration is only about half the concentration measured by the ASARCO monitor at N26th and Pearl for the hour ending at 1300 PST. Similarly, the concentrations calculated for Adams Street and the Reservoir are less than half the measured concentrations during the period 1200 to 1300 PST. However, the average concentrations for the period of fumigation agree well with the calculated concentrations.

E.2.2 Case 2: 4 May 1972 (Critical Wind-Speed Case)

During this critical wind-speed case, high SO_2 concentrations were measured at N26th and Pearl, the Reservoir and Highlands during the hour ending at 2000 PST. The ASARCO SCS did not request emissions curtailment until 1930 PST, when 78 percent curtailment was requested. The observed and calculated

SO_2 concentrations in ppm for the hour ending at 2000 PST are:

Monitor	Observed Concentration	Calculated Concentration
N26th and Pearl	(1.23)	0.88
Reservoir	0.27	0.04
Highlands	0.73	0.44

The parentheses for the observed concentration at N26th and Pearl indicate the ASARCO monitor value; no data are available for the PSAPCA monitor for this hour. It should be noted that the contributions of emissions from the non-ASARCO SO_2 sources in the Seattle-Tacoma area to the calculated concentrations are negligible.

On the average, the calculated concentrations are about half the observed concentrations. The ASARCO SO_2 emission rate used in the calculations was estimated from the ASARCO curtailment report using Equation (4-1), and we have found that the reported curtailment often does not reflect the actual emissions from the smelter. The uncertainty about the actual SO_2 emission rate helps to account for the discrepancies between calculated and observed concentrations, at least at N26th and Pearl and Highlands. Also, there are some uncertainties in the measured concentrations (note that the 1972 annual average concentrations measured by the ASARCO and PSAPCA SO_2 monitors at N26th and Pearl differ by more than a factor of 3; see Section 4.2).

E.2.3 Case 3: 4 June 1972 (Limited-Mixing Case)

Light westerly winds on the morning of 4 June 1972 shifted to northeast at midday resulting in high SO_2 concentrations in the Tacoma area for the hour ending at 1400 PST. During the period 1300 to 1330 PST, the ASARCO SCS requested 88 percent emissions curtailment; the requested curtailment was increased to 95 percent at 1330 PST. The observed and calculated SO_2 concentrations in ppm for the hour ending at 1400 PST are:

Monitor	Observed Concentration	Calculated Concentration
N26th and Pearl	0.46 (0.40)	0.25
Reservoir	0.14	0.10
Highlands	0.24	0.13

where the number enclosed by parentheses is the concentration measured by the ASARCO monitor at N26th and Pearl. Emissions from the main ASARCO stack are solely responsible for the calculated concentrations.

On the average, the calculated concentrations are about 63 percent of the observed concentrations. Based on a comparison of SO_2 emission rates estimated for other cases from Equation (4-1) and from in-stack SO_2 concentration data, it appears that Equation (4-1) significantly underestimates the SO_2 emission rate when the requested curtailment exceeds about 90 percent. Thus, it is not surprising that the observed concentrations exceed the calculated concentrations for this case.

E.2.4 Case 4: 5 July 1972 (Limited-Mixing Case)

With the ASARCO smelter operating without curtailment, the wind shifted from northwest to north-northeast during the early morning hours of 5 July 1972. Although the smelter's SCS requested 88 percent curtailment at 0220 PST, the hourly SO_2 concentrations measured at N26th and Pearl and the Reservoir exceeded the PSAPCA hourly standard of 0.40 ppm. The PSAPCA monitor at N26th and Pearl measured a concentration of 0.56 ppm, while the ASARCO monitor measured a concentration of 0.68 ppm. At the Reservoir, the ASARCO monitor measured a concentration of 0.62 ppm.

Figure E-2 shows the isopleths of ground-level SO_2 concentration produced by emissions from the main ASARCO stack calculated using the observed surface wind direction at N26th and Pearl of 007 degrees. As shown by Figure E-2, the Reservoir monitor (labeled A2 in the figure) is on the plume axis, while the N26th and Pearl station (labeled P2 and A1) is on the edge of the plume with a calculated concentration of about 0.1 ppm. Figure E-3 shows the same isopleth pattern for a mean wind direction of 010 degrees. In this case, the calculated concentrations at N26th and Pearl and the Reservoir are 0.61 and 0.64 ppm, respectively. Thus, a 3-degree shift in the surface wind direction yields calculated concentrations that are within 10 percent of the observed concentrations. If the surface wind direction had not been adjusted, the calculated concentration at N26th and Pearl would have been about 15 percent of the observed concentration and the calculated concentration at the Reservoir would have been about double the observed concentration.

Figures E-2 and E-3 clearly demonstrate the sensitivity of short-term concentrations calculated at fixed receptor points to slight changes in the wind direction used in the calculations. If the observed surface wind direction is used in the calculations, a comparison of calculated and observed concentrations often indicates an apparent failure of the short-term diffusion model. However, a slight change in the surface wind direction usually brings the calculated and observed concentrations into close agreement at all monitors. Short-term concentrations calculated at fixed receptor points are more sensitive to slight uncertainties in the wind direction than to slight uncertainties in any source or other meteorological input parameter. Thus, we believe that the procedure that we have followed in the short-term historical calculations of varying the wind direction by several degrees to find the optimum wind direction is fully warranted for the cases when two or more monitors simultaneously detected the ASARCO plume.

Figures E-2 and E-3 also indicate that the PSAPCA and ASARCO air quality monitoring networks did not detect the calculated maximum hourly ground-level SO_2 concentration for the hour ending at 0300 PST on 5 July 1972. The figures indicate that the hourly ground-level SO_2 concentration exceeded 1.0 ppm

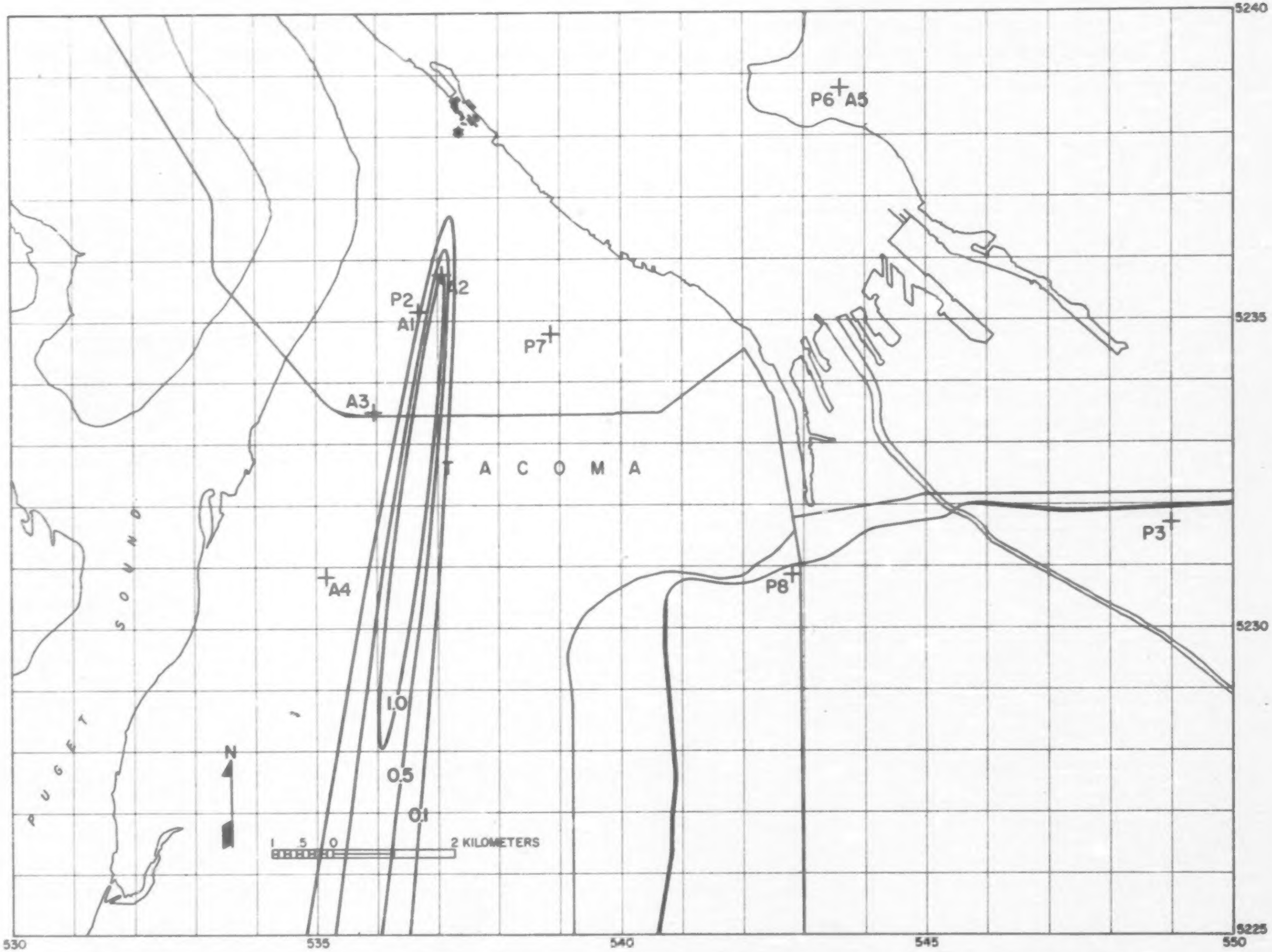

FIGURE E-2. Calculated isopleths of hourly ground-level SO_2 concentration in parts per million produced by ASARCO emissions for the hour ending at 0200 PST on 5 July 1972, assuming a wind direction of 007 degrees.

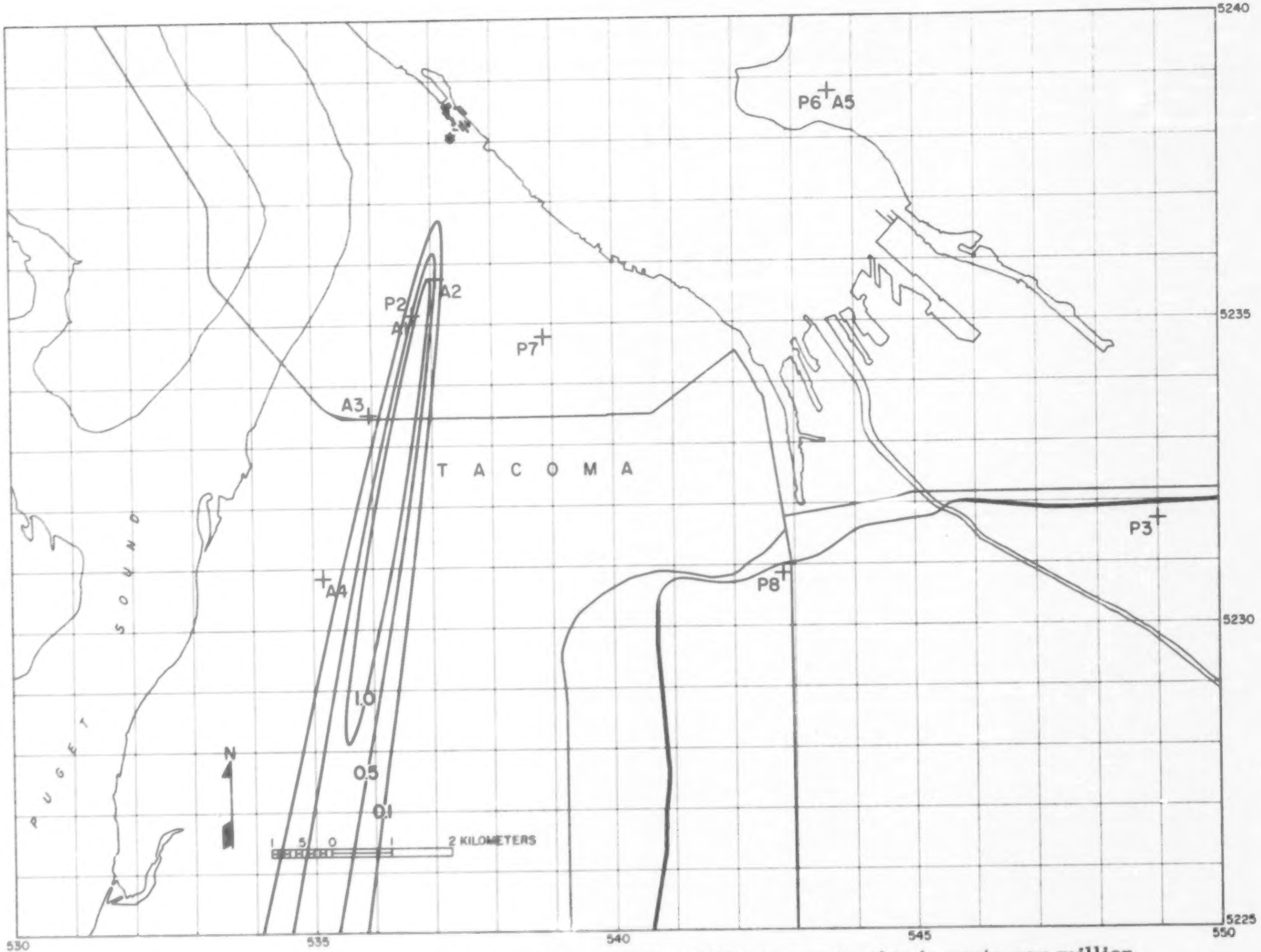

FIGURE E-3. Calculated isopleths of hourly ground-level SO_2 concentration in parts per million produced by ASARCO emissions for the hour ending at 0300 PST on 5 July 1972, assuming a wind direction of 010 degrees.

within a narrow elliptical area beginning about 2.4 kilometers from the base of the main ASARCO stack and ending about 10 kilometers from the stack. The calculated maximum hourly concentration of 1.98 ppm is located about four kilometers from the ASARCO stack.

E.2.5 Case 5: 3 October 1972 (Fumigation Case)

During the night of 2 - 3 October 1972, the ASARCO smelter operated without curtailment and with a single stack heater. Shortly before midnight, high ground-level SO_2 concentrations began to occur at N26th and Pearl, the Reservoir and Adams Street. The following SO_2 concentrations in ppm were observed:

Hour (PST)	N26th and Pearl	Reservoir	Adams St.
02/2400	0.03 (0.04)	0.08	0.01
03/0100	0.35 (0.16)	0.23	0.18
03/0200	0.05 (0.03)	0	0.01
Average	0.14 (0.08)	0.10	0.07

where the numbers enclosed by parentheses are the concentrations measured by the ASARCO monitor at N26th and Pearl.

The simultaneous occurrence of high SO_2 concentrations at the three monitors suggests a widespread fumigation. Because the high concentrations occurred in the middle of the night, solar heating obviously could not have been the cause of this fumigation. For some other reason, it appears that the mixing depth increased to above the plume height and the plume, which had been elevated, was suddenly mixed to the surface. Carlson and Scuderi (1974) report a series of diffusion experiments that included at least one trial that they believe showed this phenomenon. They hypothesize that the vertical wind shear increased until there was a sudden transfer of momentum to the surface, resulting in a fumigation.

In our calculations for this case, we assumed that the vertical turbulent intensity in the surface layer during the period of fumigation was equivalent to the median value for the Pasquill B stability category. The calculated fumigation concentrations in ppm are:

Monitor	Calculated Concentration
N26th and Pearl	0.14
Reservoir	0.13
Adams St.	0.16

ASARCO emissions account for 98 to 99 percent of these calculated concentrations. The calculated concentrations agree well with the average concentrations during the period of fumigation. However, the calculated concentrations at Adams Street and the Reservoir are about 30 percent lower than the maximum observed hourly concentrations. At N26th and Pearl, the calculated concentration is only 40 percent of the maximum hourly concentration measured by the PSAPCA monitor and about 88 percent of the maximum hourly concentration measured by the ASARCO monitor.

E.2.6 Case 6: 11 October 1972 (Critical Wind-Speed Case)

During this critical wind-speed case, high SO_2 concentrations were detected whenever the wind caused the ASARCO plume to pass over the N26th and Pearl and the Highlands SO_2 monitors. At 0215 PST, the smelter SCS turned on both heaters and requested 55 percent emissions curtailment. At 0320 PST, the SCS requested 88 percent curtailment. The following SO_2 concentrations in ppm were measured during the early morning hours of 11 October 1972:

Hour (PST)	N26th and Pearl	Highlands
0300	0.30 (0.22)	0.13
0400	0.26 (0.26)	0.05

where the numbers enclosed by parentheses are the concentrations measured by the ASARCO monitor at N26th and Pearl. The relatively low concentrations at the Highlands monitor and the near-threshold concentrations at University Place suggest that the ASARCO plume may have had a curvilinear trajectory during this period (the Highlands and University Place SO_2 monitors are on the same azimuth bearing from the ASARCO stack).

The calculated concentrations in ppm for the hours ending at 0300 and 0400 PST are:

Hour (PST)	N26th and Pearl	Highlands
0300	0.30	0.97
0400	0.23	0.04

Only emissions from the main ASARCO stack contribute significantly to the calculated concentrations. With the exception of the concentration calculated for Highlands for the hour ending at 0300 PST, the calculated and observed concentrations are in good agreement. A slight deviation of the ASARCO plume from a straight-line trajectory could easily explain the discrepancy between the calculated and observed concentrations for this monitor and hour (see Figures E-2 and E-3).

E.2.7 Case 7: 24 October 1974 (Limited-Mixing Case)

As early morning ground fog began to clear and light and variable surface winds increased and became northeasterly, high ground-level SO_2 concentrations began to occur at N26th and Pearl at about 0800 PST on 24 October 1974. The ASARCO SCS, which had previously requested 60 percent emissions curtailment, requested 88 percent curtailment at 0815 PST. Nevertheless, the hourly SO_2 concentrations measured by both monitors at N26th and Pearl exceeded the PSAPCA hourly standard of 0.40 ppm. The observed and calculated concentrations in ppm for the hour ending at 0900 PST are:

Monitor	Observed Concentration	Calculated Concentration
N26th and Pearl	0.60 (0.46)	0.26
Reservoir	0.10	0.08
Highlands	0.07	0.13

where the number enclosed by parentheses is the concentration measured by the ASARCO monitor at N26th and Pearl. As in the previous cases of northeast winds, emissions from the main ASARCO stack account for over 99 percent of the calculated concentrations.

The two concentration measurements at N26th and Pearl suggest that the SO_2 emission rate for the main ASARCO stack was about 20,000 pounds per hour rather than the rate of 10,000 pounds per hour used in the calculations. An emission rate of 20,000 pounds per hour would double the concentrations calculated at the Reservoir and Highlands, but the differences between calculated and observed concentrations would be less than the difference in the concentrations measured by the two monitors at N26th and Pearl. As noted in the following discussion of Case 8, in-stack SO_2 concentration data indicated an SO_2 emission rate of 16,000 pounds per hour during a period when 100 percent curtailment was requested. The ASARCO curtailment report and Equation (4-1) were used to estimate the emission rate of 10,000 pounds per hour for this case. Thus, it is quite possible that the SO_2 emissions during the period 0800 to 0900 PST on 24 October 1972 were about 20,000 pounds.

E.2.8 Case 8: 26 May 1973 (Limited-Mixing Case)

During the morning of 26 May 1973, surface wind directions at the various PSAPCA meteorological towers in the Tacoma area differed significantly. For example, the 1000 PST wind direction at N26th and Pearl was 250 degrees, while the wind direction at Vashon Island was 130 degrees. The average of these wind directions is 190 degrees, which is consistent with the south winds required to transport ASARCO emissions to the island (the observed concentration at Vashon Island for the hour ending at 1000 PST was 0.36 ppm). The wind shifted to north-northeast by early evening, resulting in high SO_2 concentrations in the Tacoma area. The emissions curtailment requested by the ASARCO SCS ranged from 0 to 100 percent on 26 May 1973. However, in-stack SO_2 concentration data indicate that the SO_2 emission rate was never less than about 16,000 pounds per hour for the hours included in this case.

Assuming that the wind direction at plume height was 196 degrees for the hour ending at 1000 PST, the calculated SO_2 concentration at the Vashon Island monitor is 0.44 ppm. This calculated concentration is entirely due to ASARCO emissions. Thus, ASARCO emissions could have produced the observed concentration of 0.36 ppm. However, we cannot accurately position the ASARCO plume during this hour because there is only one SO_2 monitor on Vashon Island. As previously noted, we can often estimate the wind direction at plume height to within 1 or 2 degrees when the plume is simultaneously detected by two or more monitors. In these cases, the correspondence between calculated and observed SO_2 concentrations at the various monitors usually provides strong evidence that the observed concentrations were produced by emissions from the ASARCO smelter.

On the evening of 26 May 1973, the following SO_2 concentrations in ppm were measured in the Tacoma area:

Monitor	2200 PST	2300 PST
N26th and Pearl	0.32 (0.21)	0 (0.03)
Reservoir	0.07	0.37
Highlands	0.11	0.00
University Place	0.15	0.05

where the numbers enclosed by parentheses are the concentrations measured by the ASARCO monitor at N26th and Pearl. The corresponding calculated concentrations are:

Monitor	2200 PST	2300 PST
N26th and Pearl	0.44	0.02
Reservoir	0.03	0.39
Highlands	0.22	0.00
University Place	0.21	0.00

Comparison of the calculated and observed concentrations for the hour ending at 2200 PST suggests that the SO_2 emission rate used in the calculations is about 40 percent too high. For this hour, the differences between the calculated and observed concentrations at the Reservoir (0.03 ppm) and at Highlands (0.11 ppm) are less than or equal to the difference in the concentrations measured by the ASARCO and PSAPCA SO_2 monitors at N26th and Pearl. For the hour ending at 2300 PST, the calculated and observed concentrations at the Reservoir are in excellent agreement; the calculated and observed concentrations at N26th and Pearl, Highlands and University Place are all near the threshold of the SO_2 monitors.

E.2.9 Case 9: 4 June 1973 (Limited-Mixing Case)

Low clouds and fog covered the Tacoma area on the morning of 4 June 1973. High SO_2 concentrations began to occur at the N26th and Pearl SO_2 monitors at about 0600 PST and the ASARCO SCS requested 100 percent emissions curtailment at 0625 PST. However, in-stack SO_2 concentration data indicate that over 25,000 pounds of SO_2 were emitted during the period 0600 to 0700 PST. The early morning fog and low clouds cleared by mid-morning, leading to unstable meteorological conditions with light and variable winds. Consequently, the ASARCO SCS requested emissions curtailment ranging from 88 to 100 percent throughout the morning.

For the hours ending at 0700 and 1100 PST on 4 June 1973, the observed SO_2 concentrations in ppm were:

Monitor	0700 PST	1100 PST
N26th and Pearl	0.37 (0.67)	0.31 (0.21)
Reservoir	0.00	0.23
Highlands	0.13	0.08
University Place	0.00	0.03

where the numbers enclosed by parentheses are the concentrations measured by the ASARCO monitor at N26th and Pearl. The corresponding calculated concentrations are:

Monitor	0700 PST	1100 PST
N26th and Pearl	0.64	0.11
Reservoir	0.20	0.13
Highlands	0.26	0.05
University Place	0.19	0.03

For the hour ending at 0700 PST, the calculated concentration for N26th and Pearl is in very good agreement with the concentration measured by the ASARCO monitor. However, the calculated and observed concentrations at the other monitors are not in good agreement. We have no explanation for the low observed concentrations at the Reservoir, Highlands and University Place, but the differences between the calculated and observed concentrations at these monitors are less than the difference in the concentrations measured by the collocated monitors at N26th and Pearl.

For the hour ending at 1100 PST, comparison of the calculated and observed concentrations at N26th and Pearl, the Reservoir and Highlands suggests that the SO_2 emission rate of 4,400 pounds per hour estimated from the in-stack SO_2

concentration data and used in the calculations is only about 57 percent of the actual emission rate during this period. The calculated and observed concentrations at University Place are so near the monitor threshold that a direct comparison of these concentrations is likely to be misleading.

E.2.10 Case 10: 19 June 1973 (Limited-Mixing Case)

Broken to overcast middle clouds covered the Tacoma area until late afternoon on 19 June 1973. The ASARCO SCS requested emissions curtailment ranging from 60 to 88 percent between 0700 and 1740 PST, at which time curtailment was ended. At about 2000 PST the wind shifted from northeast to north-northeast and high SO_2 concentrations began to occur at the SO_2 monitors in Tacoma. The ASARCO SCS ordered 100 percent curtailment at 2015 PST and, as concentrations began to decrease, the requested curtailment was changed to 37 percent at 2045 PST. In-stack SO_2 concentration data indicate that the main ASARCO stack emitted about 17,000 pounds of SO_2 between 2000 and 2100 PST. For the hour ending at 2100 PST, the observed and calculated SO_2 concentrations in ppm are:

Monitor	Observed Concentration	Calculated Concentration
N26th and Pearl	0.25 (0.25)	0.34
Reservoir	0.07	0.01
Highlands	0.07	0.09
University Place	0.06	0.08

where the number enclosed by parentheses is the concentration measured by the ASARCO monitor at N26th and Pearl.

Excluding the Reservoir, a comparison of the calculated and observed concentrations for each monitor indicates that the estimated SO_2 emission rate is about 33 percent higher than the actual emission rate. At the Reservoir, the calculated concentration is about 0.06 ppm lower than the observed concentration, which was only 0.07 ppm. As previously noted, concurrent concentration measurements by the collocated SO_2 monitors at N26th and Pearl frequently differ by 0.10 ppm or more.

E.2.11 Case 11: 25 July 1973 (Limited-Mixing Case)

Early morning ground fog cleared by about 1000 PST on 25 July 1973, followed by moderately unstable meteorological conditions. With light northeast to north-northeast winds, appreciable SO_2 concentrations began to occur at the SO_2 monitors in Tacoma at about 1000 PST. The ASARCO SCS requested emissions curtailment of 87 to 98.5 percent during the morning and afternoon, and in-stack SO_2 concentration data indicate that SO_2 emissions from the main stack were reduced to about 6,000 pounds per hour. The following SO_2 concentrations in ppm were observed in the Tacoma area at midday:

Monitor	1100 PST	1200 PST	1300 PST
N26th and Pearl	0.11 (0.19)	0.13 (0.23)	0.09 (0.15)
Reservoir	0.14	0.00	0.00
Highlands	0.02	0.08	0.04
University Place	0.01	0.07	0.05

where the numbers enclosed by parentheses are the concentrations measured by the ASARCO monitor at N26th and Pearl. The corresponding calculated concentrations in ppm are:

Monitor	1100 PST	1200 PST	1300 PST
N26th and Pearl	0.20	0.12	0.08
Reservoir	0.16	0.05	0.02
Highlands	0.09	0.08	0.08
University Place	0.05	0.04	0.04

For the hour ending at 1100 PST, the calculated and observed concentrations at N26th and Pearl and the Reservoir are in good agreement if the measurement by the ASARCO monitor at N26th and Pearl is assumed to be more representative than the measurement by the collocated PSAPCA monitor. The measured concentrations at Highlands and University Place are so close to the monitor threshold that a comparison of calculated and observed concentrations is likely to be misleading. However, the differences between the calculated and observed concentrations at these sites are less than the difference in the concentrations measured by the two monitors at N26th and Pearl during this hour.

For the hour ending at 1200 PST, the calculated and observed concentrations at Highlands and at N26th and Pearl are in good agreement if the measurement by the PSAPCA monitor at N26th and Pearl is assumed to be more representative than the measurement by the ASARCO monitor. It should be noted that the observed concentrations at the Reservoir, Highlands and University Place are quite low, and the differences between the calculated and observed concentrations at the Reservoir and University Place are about half the difference between the two observed concentrations at N26th and Pearl.

For the hour ending at 1300 PST, the observed concentrations at the Reservoir, Highlands and University Place are so low that a comparison of calculated and observed concentrations is probably not warranted. At N26th and Pearl, the calculated concentration is about 10 percent lower than the concentration measured by the PSAPCA monitor and about half the concentration measured by the ASARCO monitor.

E.2.12 Case 12: 30 July 1973 (Limited-Mixing Case)

On occasion, the ASARCO plume can affect the ambient air quality at long distances from the smelter. For example, the PSAPCA SO_2 monitors at McMicken Heights and Tukwila are affected by ASARCO SO_2 emissions during periods of sustained southwest winds. The McMicken Heights monitor is about 23.7 kilometers northeast of the main ASARCO stack and the Tukwila monitor is about 26.0 kilometers northeast of the stack. Because the delay time in the transport of ASARCO emissions to these monitors is typically several hours, the ASARCO SCS must anticipate the onset of conditions leading to high concentrations at these monitors and must curtail emissions several hours in advance. If the SCS fails to anticipate adverse meteorological conditions and does not curtail emissions until after the high concentrations begin to occur, high concentrations tend to persist for a time approximately equal to the travel time between the smelter and the monitors.

On 30 July 1973, southwest winds during the early morning hours carried the ASARCO plume northeast toward the McMicken Heights and Tukwila monitors. The mean wind speed at plume height was about 2 meters per second so that the dealy time in the transport of ASARCO emissions to the monitor was at least 3 hours. Taking this delay into account, the in-stack SO_2 concentration data indicate that the effective SO_2 emission rate was about 30,000 pounds per hour during the period 0800 to 1000 PST. Although the emissions curtailment requested by the ASARCO SCS was increased from 56 to 74 percent at 0800 PST, it was too late to preclude high hourly SO_2 concentrations at McMicken Heights and Tukwila. The following SO_2 concentrations in ppm were observed at the two monitors:

Monitor	0900 PST	1000 PST
McMicken Heights	0.50	0.23
Tukwila	0.18	0.13

The corresponding calculated concentrations in ppm are:

Monitor	0900 PST	1000 PST
McMicken Heights	0.52	0.16
Tukwila	0.31	0.06

These calculated concentrations are entirely due to ASARCO emissions.

The calculated concentrations for the hour ending at 0900 PST are in good agreement with the observed concentrations. The agreement between calculated and observed concentrations for the hour ending at 1000 PST is not nearly as good as the agreement for the preceding hour. However, the differences between the calculated and observed concentrations are less than the differences in concurrent observed concentrations that frequently occur for the collocated SO_2 monitors at N26th and Pearl.

E.2.13 Case 13: 31 July 1973 (Limited-Mixing Case)

West winds during the early morning hours of 31 July 1973 transported the ASARCO plume toward the PSAPCA Meeker and the ASARCO Meeker-Brown SO_2 monitors. At 0520 PST the ASARCO SCS requested 100 percent emissions curtailment; the requested curtailment was reduced to 94 percent at 0600 PST. The in-stack SO_2 concentration data indicate that the SO_2 emission rate slowly decreased from about 25,000 pounds per hour to about 6,000 pounds per hour during the next 3 hours. Because of the delay time required to reduce emissions and the approximate 1-hour travel time to the Meeker monitors, high concentrations persisted until the wind shifted to the southwest shortly before 0700 PST. With the onset of southwest winds, high concentrations began to occur at the McMicken Heights and Tukwila monitors sometime after 0800 PST.

The observed SO_2 concentrations in ppm at the Meeker SO_2 monitors during the early morning hours of 31 July 1973 were:

Hour (PST)	Meeker	Meeker-Brown
0500	0.28	0.31
0600	0.38	0.42
0700	0.59	0.49

Although the Meeker and Meeker-Brown SO_2 monitors are in such close proximity that they are shown as being in the same location in Figure E-1, we used the 180-meter separation to estimate the wind direction at plume height to within about 1 degree. Assuming a 1-hour travel time to the Meeker monitors, the calculated concentrations in ppm are:

Hour (PST)	Meeker	Meeker-Brown
0500	0.28	0.35
0600	0.42	0.50
0700	0.56	0.53

All of the calculated concentrations are within 20 percent of the observed concentrations. On the average, the calculated concentrations are about 8 percent higher than the observed concentrations. It should be noted that ASARCO is the only source that contributes to the calculated concentrations.

The observed SO_2 concentrations in ppm at the McMicken Heights and Tukwila SO_2 monitors were:

Hour (PST)	McMicken Heights	Tukwila
0900	0.16	0.12
1000	0.14	0.19

Assuming a travel time to these monitors of about 3 hours, the corresponding calculated concentrations in ppm are:

Hour (PST)	McMicken Heights	Tukwila
0900	0.21	0.05
1000	0.13	0.20

The correspondence between calculated and observed concentrations for the hour ending at 0900 PST is only fair, although the maximum difference between calculated and observed concentrations is only 0.07 ppm. For the hour ending at 1000 PST, the calculated and observed concentrations are in very good agreement. As in the previous short-term calculations for McMicken Heights and Tukwila, the calculated concentrations are entirely due to ASARCO emissions.

E.2.14 Case 14: 17 October 1973 (Limited-Mixing Case)

Light and variable surface winds during the morning of 17 October 1973 changed to light southwest winds by late morning and high SO_2 concentrations began to occur at McMicken Heights and Tukwila at about 1200 PST. At 1230 PST the ASARCO SCS requested that emissions curtailment be increased from 37 to 55 percent. Nevertheless, the observed SO_2 concentration at Tukwila for the hour ending at 1300 PST exceeded the PSAPCA hourly standard of 0.40 ppm. The observed and calculated SO_2 concentrations in ppm for the hour ending at 1300 PST are:

Monitor	Observed Concentration	Calculated Concentration
McMicken Heights	0.30	0.09
Tukwila	0.41	0.10

The calculated concentrations assume that the travel time from the ASARCO smelter to the two monitors was about 2 hours on 17 October 1973.

Of all of the historical cases for the limited-mixing condition, this case has the poorest correspondence between calculated and observed concentrations. Assuming the validity of the SO_2 emission rate estimated from the in-stack SO_2 concentration data, it appears that the meteorological inputs used in the calculations are not representative of the actual conditions during the period 1200 to 1300 PST.

The early morning Portage Bay EMSU sounding showed a shallow mixing layer of about 125 meters and the 1300 PST sounding showed a deep mixing layer of about 1150 meters. The early afternoon mixing depth was used in the calculations. However, it is possible that there was a significant increase in the mixing depth between 1200 and 1300 PST. If the average mixing depth for the period was about 400 meters, the calculated and observed concentrations would be in much better agreement.

E.2.15 Case 15: 28 January 1974 (Critical Wind-Speed Case)

During this critical wind-speed case, relatively high SO_2 concentrations were measured at Maury Island during the early morning hours and again at midday. As high SO_2 concentrations began to occur at about 0200 PST on 28 January 1974, the ASARCO SCS requested 55 percent emissions curtailment. Although curtailment was reduced to 17 percent at 0230 PST, the SCS requested 55 percent curtailment and turned on the second stack heater at 0330 PST. High SO_2 concentrations again began to occur at Maury Island at about 1100 PST. Emissions curtailment requested by the ASARCO SCS during the period 1100 to 1200 PST ranged from 50 to 88 percent.

For the hours ending at 0300, 0400 and 1200 PST on 28 January 1974, the observed and calculated SO_2 concentrations in ppm at Maury Island are:

Hour (PST)	Observed Concentration	Calculated Concentration
0300	0.10	0.25
0400	0.20	0.32
1200	0.18	0.16

The calculated concentrations assume that the ASARCO plume was transported directly over the Maury Island monitor. ASARCO emissions account for 100 percent of the calculated concentrations. Because the calculated centerline concentrations are greater than or approximately equal to the measured concentrations, ASARCO emissions could easily have produced the observed SO_2 concentrations at Maury Island on 28 January 1974.

E.2.16 Case 16: 9 February 1974 (Fumigation Case)

When early morning ground fog cleared in the Tacoma area on the morning of 9 February 1974, high ground-level SO_2 concentrations occurred over a widespread area. The ASARCO SCS requested emissions curtailments of 40 percent at 0535 PST, 88 percent at 0545 PST, 50 percent at 0720 PST and 82 percent at 0830 PST. As the high SO_2 concentrations that began at about 0830 PST continued, the SCS requested 100 percent curtailment between 0900 and 1300 PST. The following SO_2 concentrations in ppm were measured in Tacoma and the surrounding area on the morning of 9 February 1974:

Monitor	1000 PST	1100 PST	1200 PST	Avg
N26th and Pearl	0.42(0.40)	0.49(0.52)	0.29(0.27)	0.40(0.40)
Maury Island	0.01	0.09	0.18	0.09
Reservoir	0.07	0.21	0.14	0.14
Highlands	0.12	0.19	0.21	0.17

where the concentrations enclosed by parentheses are the concentrations measured by the ASARCO monitor at N26th and Pearl. The calculated fumigation concentrations in ppm are:

Monitor	Calculated Concentration
N26th and Pearl	0.08
Maury Island	0.03
Reservoir	0.09
Highlands	0.06

The contribution of ASARCO emissions to the calculated concentrations ranges from 93 percent at Maury Island to 98 percent at the Reservoir and N26th and Pearl.

The calculated concentrations are about 15 to 45 percent of the maximum observed hourly concentrations and about 20 to 65 percent of the average concentrations measured during the period of fumigation. In the previous fumigation cases (Cases 1 and 5), the calculated concentrations typically were about half of the maximum hourly concentrations and approximately equal to the average concentrations for the period of fumigation. The poor correspondence between the calculated fumigation concentrations and the average observed concentrations in this case suggests that the wind-direction distribution departed significantly from the circular wind-direction distribution assumed by the model. Also, the SO_2 emission rate for the ASARCO stack used in the calculation (the average rate indicated by the in-stack SO_2 data for the period 0500 to 0900 PST) may have been too low.

E.2.17 Case 17: 26 February 1974 (Limited-Mixing Case)

Broken to overcast low and middle clouds covered the Tacoma area during the early morning hours of 26 February 1974. Light rain was also reported at McChord Air Force Base during this period. The ASARCO smelter operated with one stack heater during the period 0300 to 0400 PST; the smelter's SCS did not request any emissions curtailment. The observed SO_2 concentration at Maury Island for the hour ending at 0400 PST was 0.33 ppm. Assuming that the centerline of the ASARCO plume was transported directly over the Maury Island monitor, the calculated concentration is 0.47 ppm. A 2- to 3-degree shift in the wind direction would bring the calculated and observed concentrations into exact agreement. As previously noted, when the wind blows directly from the ASARCO stack toward the Maury Island monitor, ASARCO is the only source that contributes to the concentration calculated for the monitor.

E.2.18 Case 18: 6 September 1974 (Limited-Mixing Case)

Northeast winds and unstable meteorological conditions during the afternoon of 6 September 1974 caused the ASARCO SCS to request emissions curtailment ranging from 97 to 100 percent. Nevertheless, relatively high SO_2 concentrations were measured in the Tacoma area during the period 1500 to 1600 PST. The observed and calculated SO_2 concentrations in ppm are:

Monitor	Observed Concentration	Calculated Concentrations
N26th and Pearl	0.23(0.21)	0.20
Reservoir	0.09	0.10
Highlands	0.08	0.14

where the number enclosed by parentheses is the concentration measured by the ASARCO monitor at N26th and Pearl.

This is one of the two hours included in the 20 Short-Term Historical Cases when we believe that sea-breeze fumigation as described by Lyons and Cole (1973) may have been occurring. However, the correspondence between the observed concentrations and the concentrations calculated using the short-term diffusion model described in Section A.3 of Appendix A is excellent.

E.2.19 Case 19: 7 October 1974 (Limited-Mixing Case)

High SO_2 concentrations were measured in the Tacoma area during the early morning of 7 October 1974 and again during the early afternoon. After high concentrations began to occur at about 0100 PST, the ASARCO SCS requested 100 percent emissions curtailment at 0145 PST. The requested curtailment was reduced to 60 percent at 0230 and ended at 0315 PST. During the late morning and early afternoon of 7 October 1974, the ASARCO SCS requested emissions curtailment ranging from 84 to 96 percent. The following concentrations in ppm were measured in the Tacoma area on 7 October 1974:

Monitor	0200 PST	1200 PST	1300 PST
N26th and Pearl	0.42(0.35)	0.27(0.17)	0.14(0.11)
Reservoir	0.50	0.03	0.02
Highlands	0.02	0.13	0.13
University Place	0.01	0.12	0.08

where the numbers enclosed by parentheses are the concentrations measured by the ASARCO monitor at N26th and Pearl. The corresponding calculated concentrations in ppm are:

Monitor	0200 PST	1200 PST	1300 PST
N26th and Pearl	0.87	0.10	0.14
Reservoir	1.00	0.04	0.02
Highlands	0.01	0.07	0.16
University Place	0.00	0.04	0.09

A comparison of the calculated and observed concentrations for the hour ending at 0200 PST suggests that the SO_2 emission rate used in the calculations is about double the actual emission rate. The emission rate used in the calculation was estimated from Equation (2-1) and, as noted in Section 2.1, the emission rate obtained from Equation (2-1) may differ from the actual emission rate by about 20 percent. Also, the average in-stack SO_2 concentration for this hour is one of the highest that we have seen for the smelter operating at 51 percent permanent control. Because the ratios of calculated and observed concentrations at N26th and Pearl and the Reservoir are nearly identical, we believe that this case demonstrates the uncertainty in the ASARCO smelter's hourly SO_2 emission rate rather than a failure of the short-term diffusion model.

For the hour ending at 1200 PST, the calculated concentrations are only about one-third to one-half the observed concentrations. This hour may also illustrate an uncertainty in the SO_2 emission rate. However, the differences between the calculated and observed concentrations are less than the difference in the concentrations observed by the two monitors at N26th and Pearl.

The hour ending at 1300 PST is the second hour when we believe that sea-breeze fumigation as described by Lyons and Cole (1973) may have been occurring. As in the other case of possible sea-breeze fumigation, the correspondence between the observed concentrations and the concentrations calculated using the short-term diffusion model described in Section A.3 of Appendix A is excellent. Thus, it is not necessary to invoke the concept of sea-breeze fumigation in order to explain the observed concentrations.

E.2.20 Case 20: 25 December 1974 (Limited-Mixing Case)

We selected 25 December 1974 for study because there were no SCS activities at the ASARCO smelter throughout the entire 24-hour period (i.e., no stack heaters were used and no emissions curtailment was requested). Table E-2 lists the meteorological input parameters used in the calculations for 25 December 1974. The wind speeds and wind directions in Table E-2 are the values measured at N26th and Pearl, except that Maury Island wind speeds and

TABLE E-2

METEOROLOGICAL INPUT PARAMETERS FOR 25 DECEMBER 1974

Hour (PST)	Wind Direction (deg)	Wind Speed (m/sec)	Ambient Air Temperature (°K)	Potential Temperature Gradient (°K/m)	Mixing Depth (m)	Wind Profile Exponent p	Pasquill Stability Category
0100	212	3.807	279	0.004	875	0.15	D
0200	241	4.424	278	0.004	875	0.15	D
0300	216	5.196	277	0.004	875	0.15	D
0400	217	5.813	277	0.004	875	0.10	D
0500	220	4.373	277	0.004	875	0.20	E
0600	254	2.829	277	0.004	875	0.25	E
0700	223	3.138	276	0.004	875	0.20	E
0800	207	3.395	274	0.004	875	0.15	D
0900	206	1.595	275	0.004	875	0.20	D
1000	214	1.440	277	0.004	875	0.20	C
1100	204	2.161	279	0.004	875	0.15	C
1200	257	1.749	280	0.004	875	0.15	C
1300	272	1.440	280	0.004	875	0.20	C
1400	325	1.080	279	0.004	875	0.20	C
1500	335	0.823	279	0.004	875	0.20	C
1600	296	1.029	278	0.004	875	0.20	C
1700	274	1.183	278	0.004	875	0.25	D
1800	226*	1.235*	278	0.004	875	0.25	D
1900	234*	1.440*	278	0.004	875	0.25	D
2000	224	0.823	278	0.004	875	0.25	D
2100	149*	1.440*	277	0.004	875	0.30	E
2200	232	0.772	277	0.004	875	0.25	D
2300	149*	1.595*	276	0.004	875	0.20	D
2400	139*	1.595*	276	0.004	875	0.25	D

* Wind direction and wind speed measured at Maury Island; N26th and Pearl winds were variable.

wind directions are listed for the hours (1800, 1900, 2100, 2300 and 2400 PST) when the winds at N26th and Pearl were reported as variable. No attempt was made to estimate the hourly wind directions at plume height; the wind directions in Table E-2 are unadjusted surface wind directions. The N26th and Pearl (or Maury Island) wind speeds were used in combination with cloud-cover observations at McChord Air Force Base to assign the Pasquill Stability Category to each hour following the Turner (1964) procedures. The mixing depths and potential temperature gradients obtained from the Portage Bay EMSU soundings on the mornings of 24 and 26 December 1974 were averaged and assumed to apply throughout 25 December 1974. Because broken to overcast low and middle clouds covered the Tacoma area during most of this period, it is reasonable to assume that there was little diurnal variation of either the mixing depth or the potential temperature gradient. Table E-3 lists the emissions data for the main ASARCO stack on 25 December 1974. Although no emissions curtailment was requested on 25 December 1974, Table E-3 indicates that there were significant hour-to-hour variations in the SO_2 emission rate (Equation (2-1) was used to calculate the hourly SO_2 emission rates given in the table).

Figure E-4 shows the calculated isopleths of 24-hour average ground-level SO_2 concentration in ppm for 25 December 1974. The concentration isopleths in Figure E-4 include the calculated effects of all major SO_2 sources in the Seattle-Tacoma area. Table E-4 lists the calculated maximum hourly and 24-hour average ground-level SO_2 concentrations for 25 December 1974. ASARCO emissions account for 99.5 to 100 percent of the calculated concentrations listed in Table E-4. The calculated maximum 24-hour average concentration is located approximately 6.8 kilometers northeast of the main ASARCO stack. This concentration is below the National and PSAPCA 24-hour Air Quality Standards of 0.14 and 0.10 ppm, respectively. However, the calculations indicate that the PSAPCA hourly standard of 0.40 ppm (never to be exceeded) was exceeded during 21 hours on Christmas Day 1974. Also, the calculated maximum 3-hour concentration of 0.52 ppm slightly

TABLE E-3

EMISSIONS DATA FOR THE MAIN ASARCO STACK ON 25 DECEMBER 1974

Hour (PST)	SO_2 Emission Rate (lb/hr)	Volumetric Emission Rate (m^3/sec)	Stack Exit Temperature (^oK)
0100	28,607	260.95	346.0
0200	22,447	260.95	346.0
0300	21,607	260.95	346.0
0400	25,975	260.95	346.0
0500	30,175	260.95	346.0
0600	23,007	260.95	346.0
0700	23,567	260.95	346.0
0800	22,447	260.95	346.0
0900	18,975	260.95	346.0
1000	19,927	260.95	346.0
1100	21,495	260.95	346.0
1200	22,335	260.95	346.0
1300	21,327	260.95	346.0
1400	21,775	260.95	346.0
1500	17,407	260.95	346.0
1600	19,927	260.95	346.0
1700	20,375	260.95	346.0
1800	25,247	260.95	346.0
1900	21,887	260.95	346.0
2000	20,487	260.95	346.0
2100	21,887	260.95	346.0
2200	25,807	260.95	346.0
2300	20,207	260.95	346.0
2400	19,647	250.95	346.0

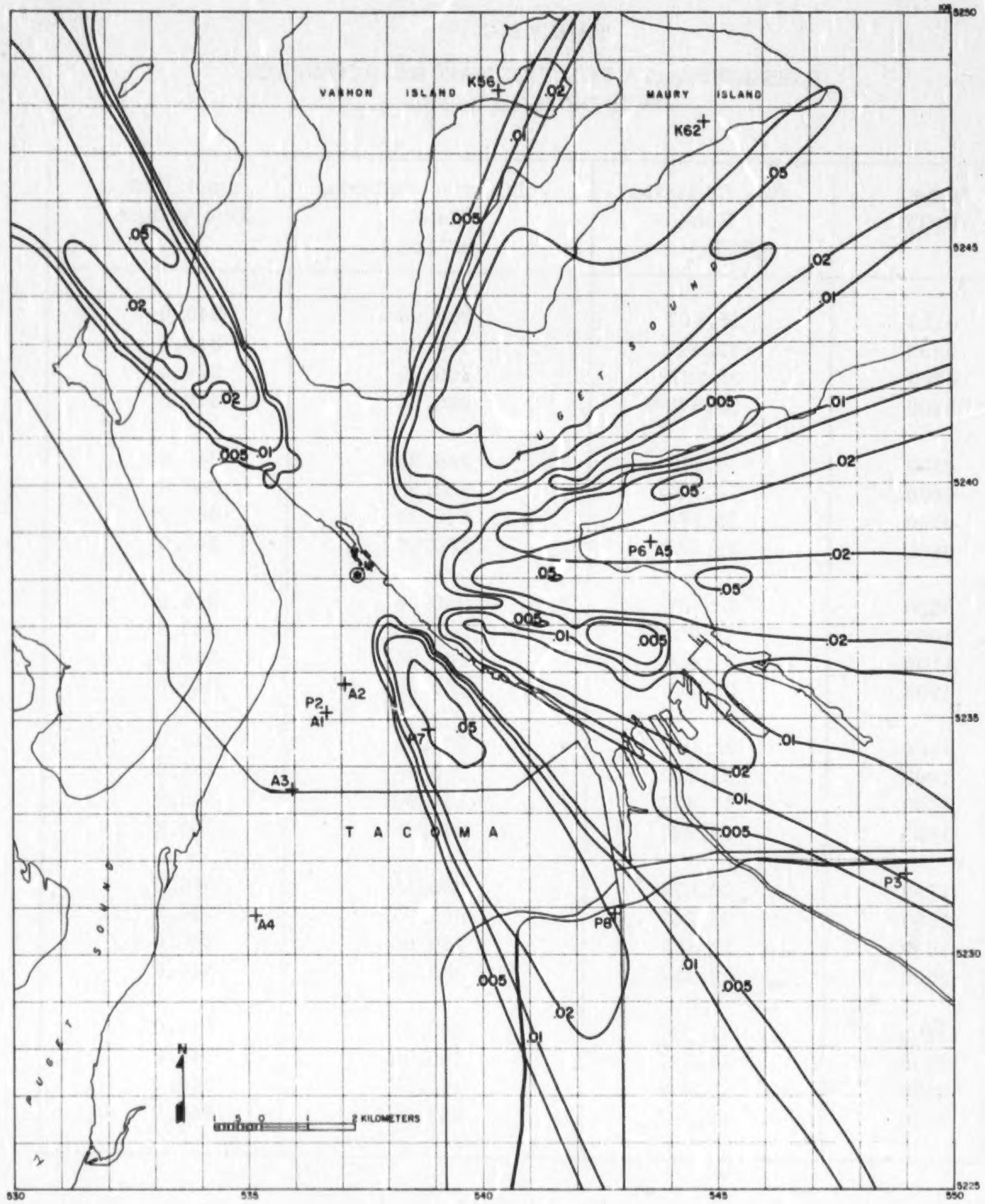

FIGURE E-4. Calculated isopleths of 24-hour average ground-level SO_2 concentration in parts per million produced by emissions from the combined sources on 25 December 1974.

TABLE E-4

LOCATIONS AND MAGNITUDES OF CALCULATED MAXIMUM HOURLY AND 24-HOUR SO_2 CONCENTRATIONS ON 25 DECEMBER 1974

Hour (PST)	Maximum Calculated Concentration (ppm)	Location	
		UTM X(m)	UTM Y(m)
0100	0.69	541,000	5,244,000
0200	0.36	542,500	5,241,000
0300	0.31	541,000	5,243,500
0400	0.35	541,000	5,243,000
0500	0.44	541,500	5,243,000
0600	0.77	544,000	5,240,000
0700	0.44	542,500	5,243,500
0800	0.41	540,000	5,243,500
0900	0.58	540,000	5,243,500
1000	0.61	540,000	5,242,000
1100	0.52	539,000	5,242,000
1200	0.66	541,500	5,239,000
1300	0.68	541,500	5,238,000
1400	1.24	539,500	5,235,000
1500	1.20	539,000	5,234,500
1600	0.75	541,500	5,236,000
1700	0.60	543,500	5,237,500
1800	0.85	542,000	5,242,500
1900	0.68	542,000	5,241,500
2000	0.90	542,000	5,243,000
2100	0.59	534,000	5,243,500
2200	1.17	543,000	5,242,500
2300	0.61	534,000	5,243,500
2400	0.73	533,000	5,243,000
24-Hour Average	0.09	542,000	5,243,000

exceeds the 3-hour Secondary Air Quality Standard of 0.50 ppm. This concentration, which is located 3.1 kilometers southeast of the ASARCO stack, is calculated for the 3-hour period ending at 1500 PST.

Table E-5 compares the calculated and observed hourly and 24-hour average SO_2 concentrations at the Maury Island, Meeker and Meeker-Brown SO_2 monitors. As shown by the table, there is poor agreement between the hour-by-hour calculated and observed concentrations at the three monitors. As previously noted, we believe that this discrepancy is principally due to a fundamental lack of accuracy in the available wind-direction data which precludes the accurate positioning of plumes with respect to specific grid points on an hourly basis. For periods of 24 hours, however, the effects of inaccuracies in the hourly meteorological data are considerably reduced by the averaging process. As indicated by Table E-6, the calculated and observed 24-hour average SO_2 concentrations at the various ASARCO and PSAPCA SO_2 monitors are in good agreement. This result is consistent with our previous experience in urban diffusion modeling (for example, Cramer, et al., 1975) and the experience of others as summarized by Pasquill (1974, p. 309).

TABLE E-5

COMPARISON OF CALCULATED AND OBSERVED CONCENTRATIONS ON 25 DECEMBER 1974

Hour (PST)	Maury Island		Meeker(Meeker-Brown)	
	Calculated Concentration (ppm)	Observed Concentration (ppm)	Calculated Concentration (ppm)	Observed Concentration (ppm)
0100	0.02	0.00	0.00(0.00)	0.00(0.00)
0200	0.00	0.06	0.00(0.00)	0.00(0.00)
0300	0.13	0.08	0.00(0.00)	0.00(0.00)
0400	0.19	0.02	0.00(0.00)	0.00(0.00)
0500	0.22	0.01	0.00(0.00)	0.00(0.00)
0600	0.00	0.01	0.00(0.00)	0.00(0.00)
0700	0.01	0.04	0.00(0.00)	0.01(0.00)
0800	0.00	0.04	0.00(0.00)	0.00(0.00)
0900	0.00	0.02	0.00(0.00)	0.00(0.00)
1000	0.17	0.26	0.00(0.00)	0.00(0.00)
1100	0.00	0.06	0.00(0.00)	0.01(0.00)
1200	0.00	0.00	0.14(0.16)	0.00(0.00)
1300	0.00	0.00	0.10(0.09)	0.00(0.00)
1400	0.00	0.00	0.00(0.00)	0.01(0.01)
1500	0.00	0.00	0.00(0.00)	0.01(0.01)
1600	0.00	0.00	0.00(0.00)	0.10(0.05)
1700	0.00	0.02	0.00(0.00)	0.03(0.03)
1800	0.00	0.25	0.00(0.00)	0.00(0.00)
1900	0.00	0.12	0.00(0.00)	0.00(0.00)
2000	0.04	0.05	0.00(0.00)	0.00(0.00)
2100	0.00	0.00	0.02(0.01)	0.00(0.00)
2200	0.00	0.00	0.00(0.00)	0.00(0.00)
2300	0.00	0.00	0.02(0.01)	0.00(0.01)
2400	0.00	0.00	0.00(0.00)	0.01(0.02)
24-Hour Average	0.03	0.04	0.01(0.01)	0.01(0.01)

TABLE E-6

COMPARISON OF CALCULATED AND OBSERVED 24-HOUR AVERAGE SO_2 CONCENTRATIONS ON 25 DECEMBER 1974

Monitor	Calculated Concentration (ppm)	Observed Concentration (ppm)
N26th and Pearl	0.00	
PSAPCA		0.00
ASARCO		0.00
Reservoir	0.00	
Highlands	0.00	0.00
University Place	0.00	0.00
Meeker Jr. H. S.	0.01	0.01
Meeker-Brown	0.01	0.01
Maury Island	0.03	0.04